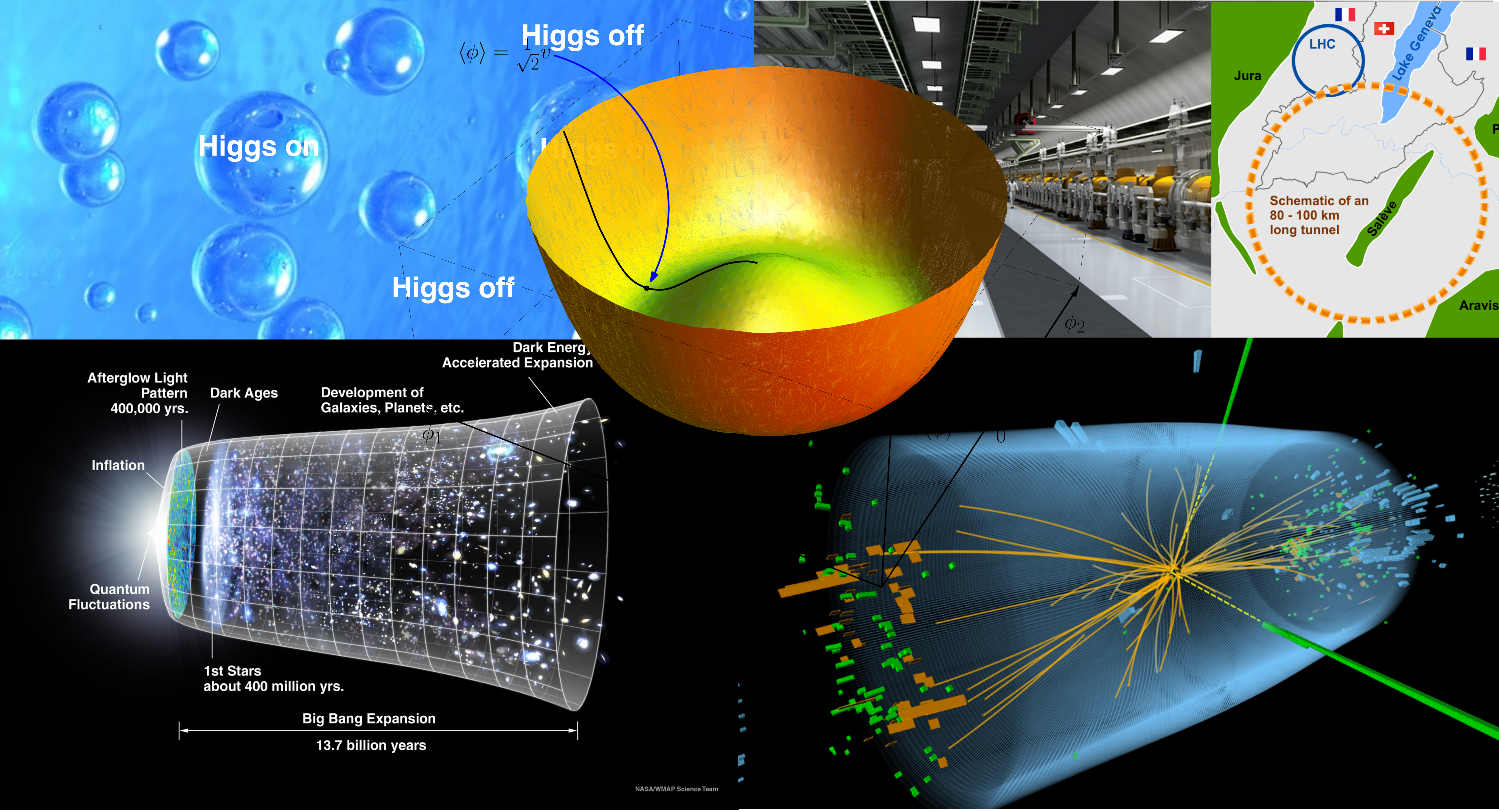

Higgs physics at future colliders

Georg Weiglein, DESY & UHH

Corfu, 05 / 2024

Universität Hamburg
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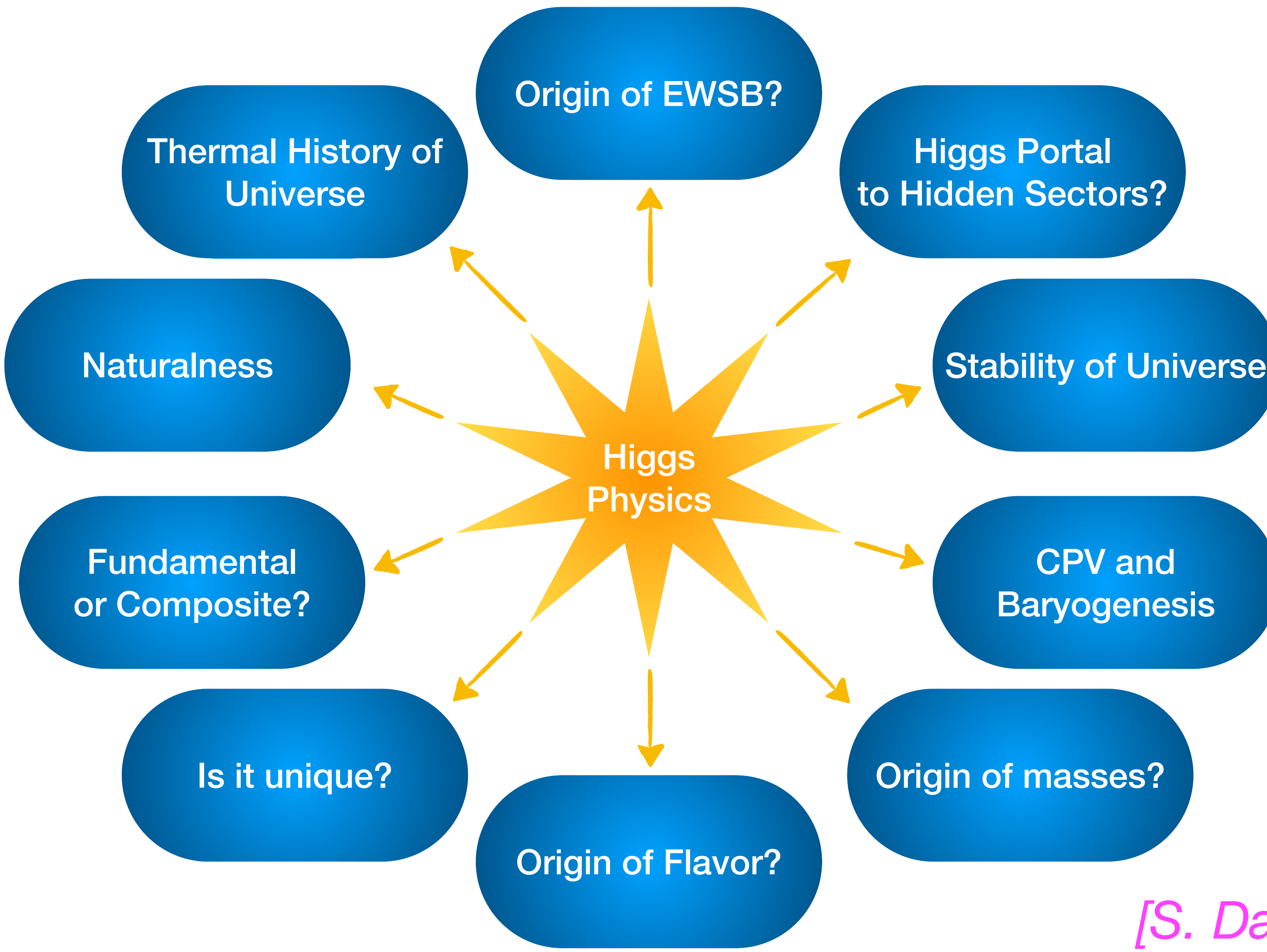
DESY.

Outline

- Introduction
- Properties of the detected Higgs boson at 125 GeV (h125)
- Higgs potential — the ``holy grail” of particle physics
- BSM Higgs bosons
- Conclusions

Introduction

Most of the open questions of particle physics are directly related to Higgs physics and in particular to the Higgs potential



[S. Dawson et al. '22]

Unsolved issues in the Higgs sector

[J. Braathen '24]

Slide adapted from [Salam '23], itself adapted from [Giudice]

$$\mathcal{L} \supset -\frac{1}{4} F^a_{\mu\nu} F^{a,\mu\nu} + \bar{\psi}_i \gamma_\mu D^\mu_{ij} \psi_j$$

→ entirely constrained by gauge symmetry, tested to high precision (e.g. LEP)

$$\mathcal{L} \supset -y_{ij} \bar{\psi}_i \Phi \psi_j + \mu^2 |\Phi|^2 + \lambda |\Phi|^4 - V_0$$

Yukawa couplings: Hierarchy of fermion masses and flavour

Higgs mass term: Gauge hierarchy problem

Quartic Higgs coupling: UV behaviour and vacuum stability *(more later)*

Vacuum energy: Cosmological constant problem

Possible relations of the Higgs and the dark sector

Higgs decays into dark matter particles would give rise to a ``missing energy” signature and give rise to an ``invisible” decay mode

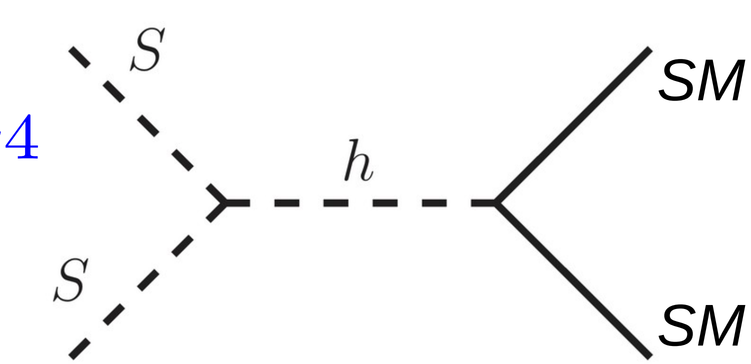
The Higgs boson(s) could also act as a ``mediator” between the visible and the dark sector

The Higgs sector as a ``portal” to the dark sector:

- $|\Phi|^2$ is a gauge singlet → Higgs field provides a perfect way to write a **portal term** in the Lagrangian, *[J. Braathen ’24]*
  e.g. simplest example = add to SM a singlet S, charged under a global Z_2 symmetry to stabilise DM

$$\mathcal{L}_{\mathbb{Z}_2\mathrm{SSM}} = \mathcal{L}_{\mathrm{SM}} - \lambda_{\mathrm{portal}} S^2 |\Phi|^2 - \lambda_{\mathrm{dark}} S^4$$

$\lambda_{\mathrm{portal}}$: *controls DM relic density & detection*



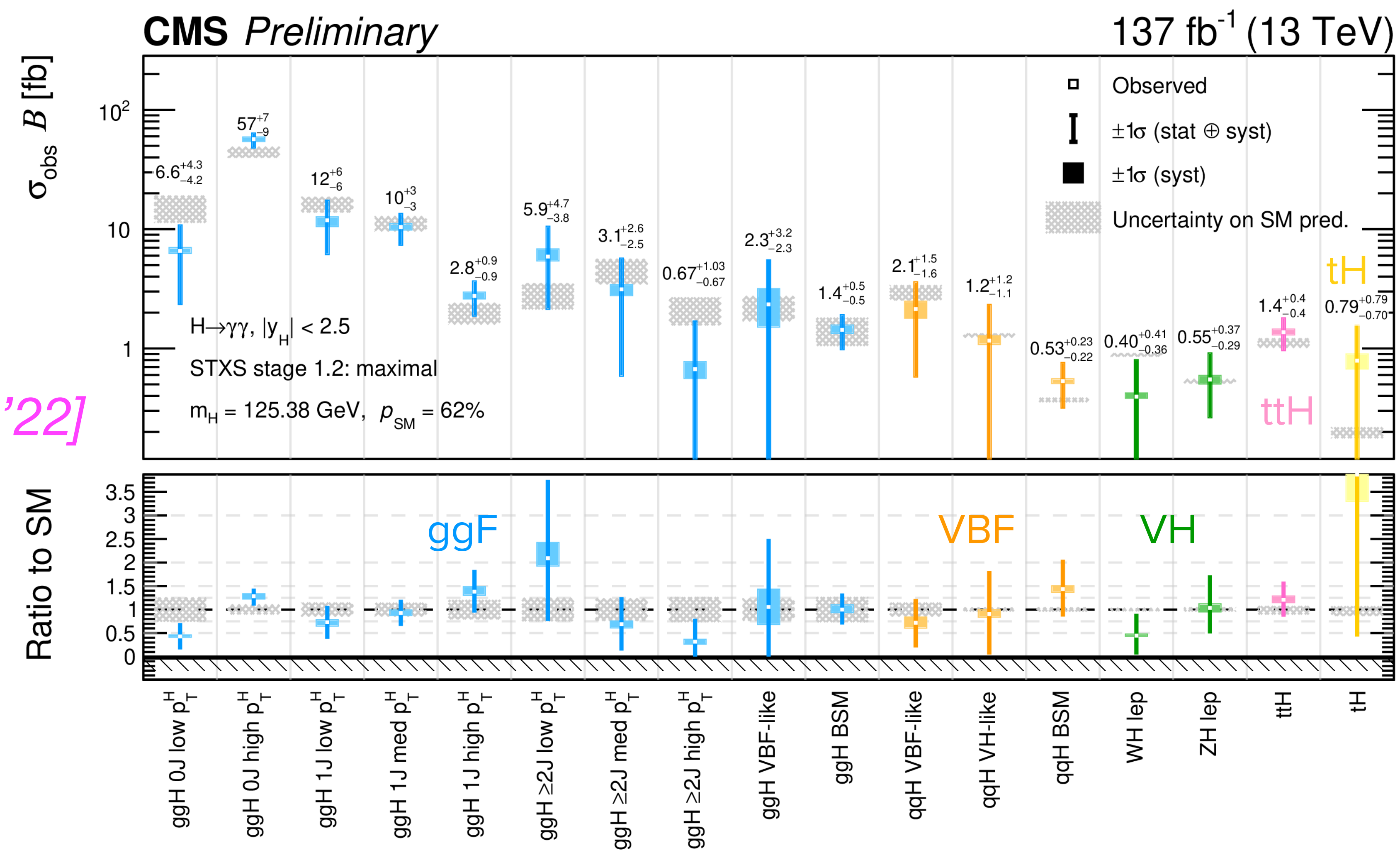
- Plethora of models: inert singlets, doublets, triplets; Next-to-Two-Higgs-Doublet Model (N2HDM), S2HDM, etc.

Properties of the detected Higgs boson (h125)

The Standard Model of particle physics uses a ``minimal” form of the Higgs potential with a single Higgs boson that is an elementary particle

h125: inclusive and differential rates

[CMS Collaboration ’22]



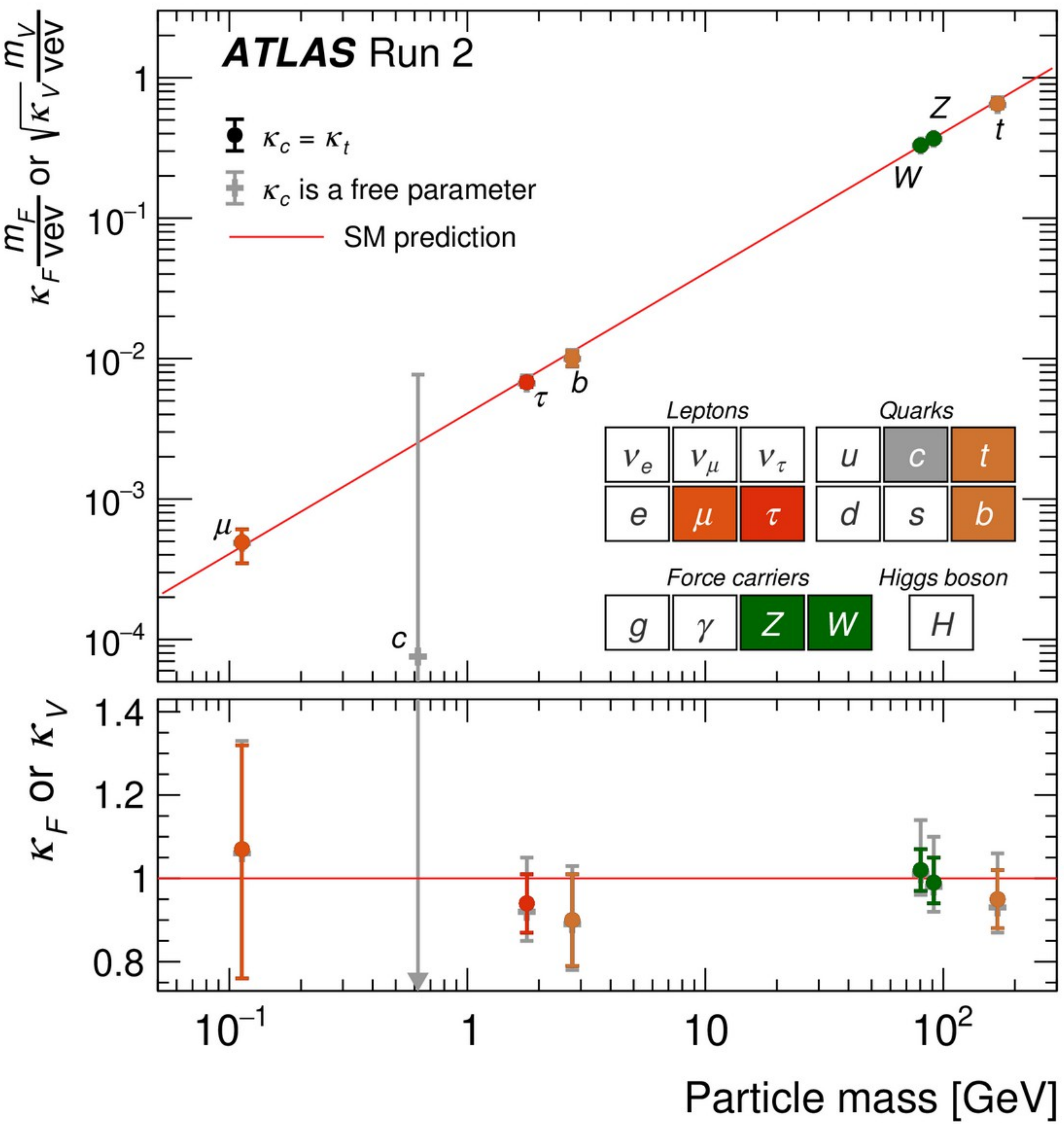
⇒SM-like properties

The LHC results on the discovered Higgs boson within the current uncertainties are compatible with the predictions of the Standard Model, but also with a wide variety of other possibilities, corresponding to very different underlying physics

Properties of the detected Higgs boson (h125)

Couplings of the detected Higgs boson to other particles:

[ATLAS Collaboration '22]



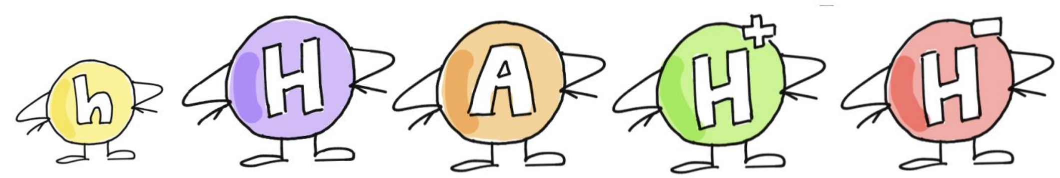
Nobel Prize 2013

⇒ Agrees with predictions of the Brout-Englert-Higgs (BEH) mechanism

Simple example of extended Higgs sector: 2HDM

Two Higgs doublet model (2HDM):

- **CP conserving** 2HDM with two complex doublets: $\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1+\rho_1+i\eta_1}{\sqrt{2}} \end{pmatrix}, \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2+\rho_2+i\eta_2}{\sqrt{2}} \end{pmatrix}$



[K. Radchenko '23]

- **Softly broken $\mathbb{Z}_2$ symmetry** ($\Phi_1 \to \Phi_1$; $\Phi_2 \to -\Phi_2$) entails 4 Yukawa types

- Potential:

$$V_{\rm 2HDM} = m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}((\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2),$$

- Free parameters: $m_h, m_H, m_A, m_{H^\pm}, m_{12}^2, \tan\beta, \cos(\beta-\alpha), v$

$\tan\beta = v_2/v_1$
$v^2 = v_1^2 + v_2^2 \sim (246 \text{ GeV})^2$

In alignment limit, $\cos(\beta - \alpha) = 0$: h couplings are SM-like at tree level

Masses of the BSM Higgs fields

$$m_A^2 = [m_{12}^2/(v_1 v_2) - 2\lambda_5]\,(v_1^2 + v_2^2) \qquad m_+^2 = [m_{12}^2/(v_1 v_2) - \lambda_4 - \lambda_5]\,(v_1^2 + v_2^2)$$

In general: BSM Higgs fields receive contributions from two sources:

$$m_\Phi^2 = M^2 + \tilde{\lambda}_\Phi v^2\,, \quad \Phi \in \{H, A, H^\pm\}$$

where $M^2 = 2\, m_{12}{}^2/\sin(2\beta)$

Sizeable splitting between m_Φ and M induces large BSM contributions the the Higgs self-couplings (see below)

SMEFT: parametrising possible deviations from the SM

Effective Lagrangian approach, obtained from integrating out heavy particles

Assumption: new physics only appears at scale $\Lambda \gg M_h \approx 125$ GeV

Systematic approach: expansion in inverse powers of Λ; parametrises deviations of coupling strenghts and tensor structure

$$\Delta\mathcal{L} = \sum_i \frac{a_i}{\Lambda^2} \mathcal{O}_i^{d=6} + \sum_j \frac{a_j}{\Lambda^4} \mathcal{O}_j^{d=8} + \ldots$$

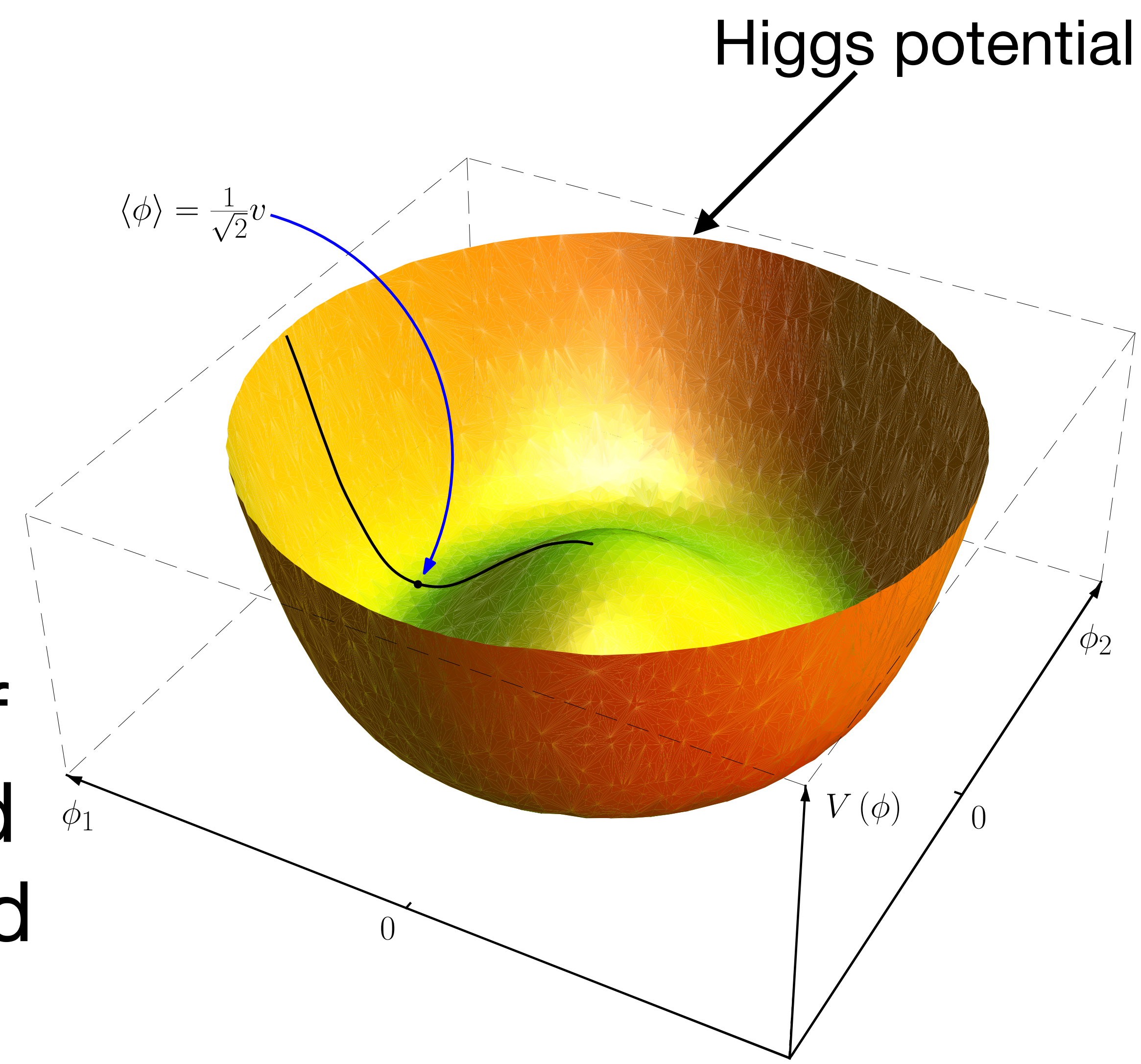
How about light BSM particles?

Difficult to incorporate in a generic way, need full structure of particular models

What is the underlying dynamics of electroweak symmetry breaking?

The vacuum structure is caused by the Higgs field through the Higgs potential. We lack a deeper understanding of this!

We do not know where the Higgs potential that causes the structure of the vacuum actually comes from and which form of the potential is realised in nature. Experimental input is needed to clarify this!



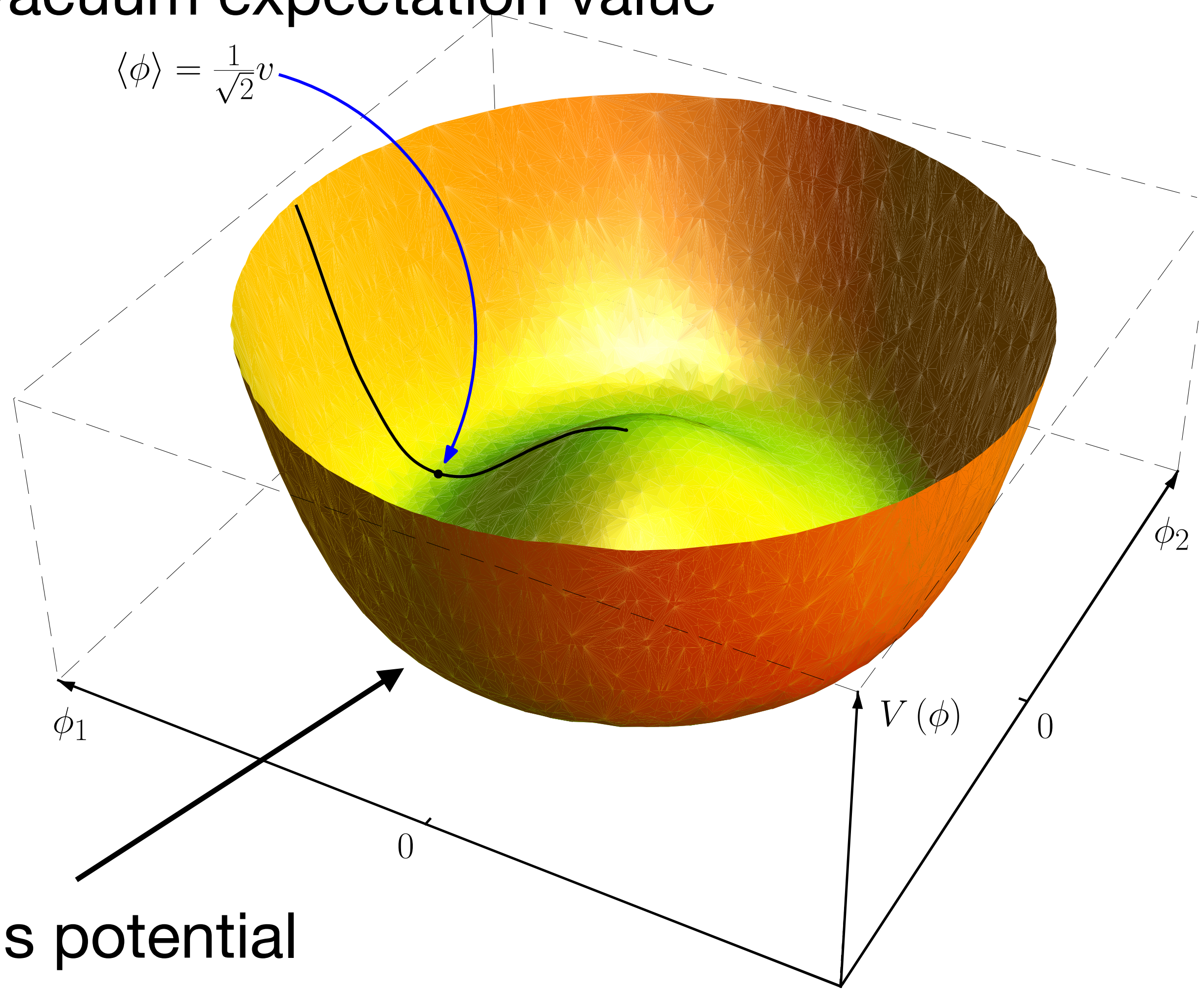
Single doublet or extended Higgs sector? (new symmetry?)

Fundamental scalar or compositeness? (new interaction?)

Higgs potential: the "holy grail" of particle physics

Crucial questions related to electroweak symmetry breaking: what is the form of the Higgs potential and how does it arise?

Vacuum expectation value



Higgs potential

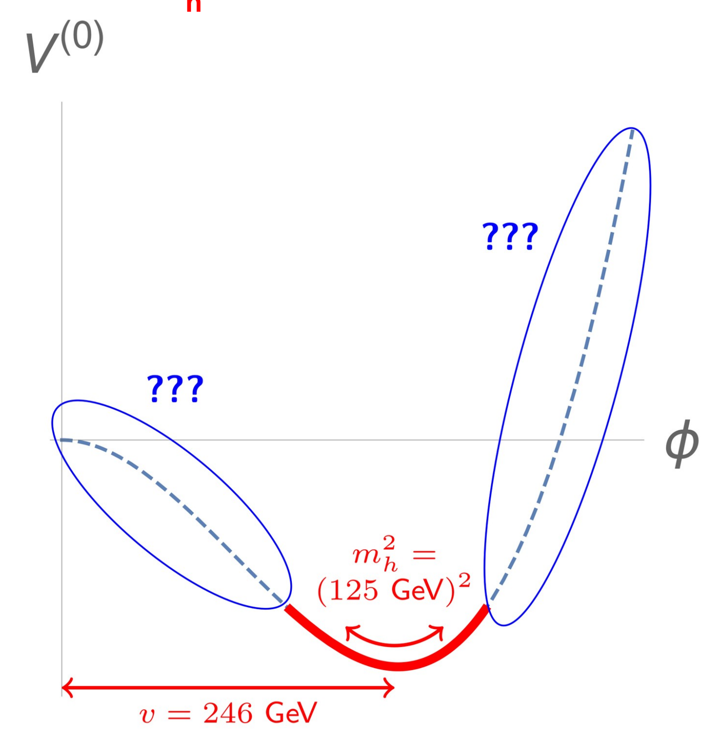
Only known so far:

→ the location of the EW minimum:

v = 246 GeV

→ the curvature of the potential around the EW minimum:

m_h = 125 GeV



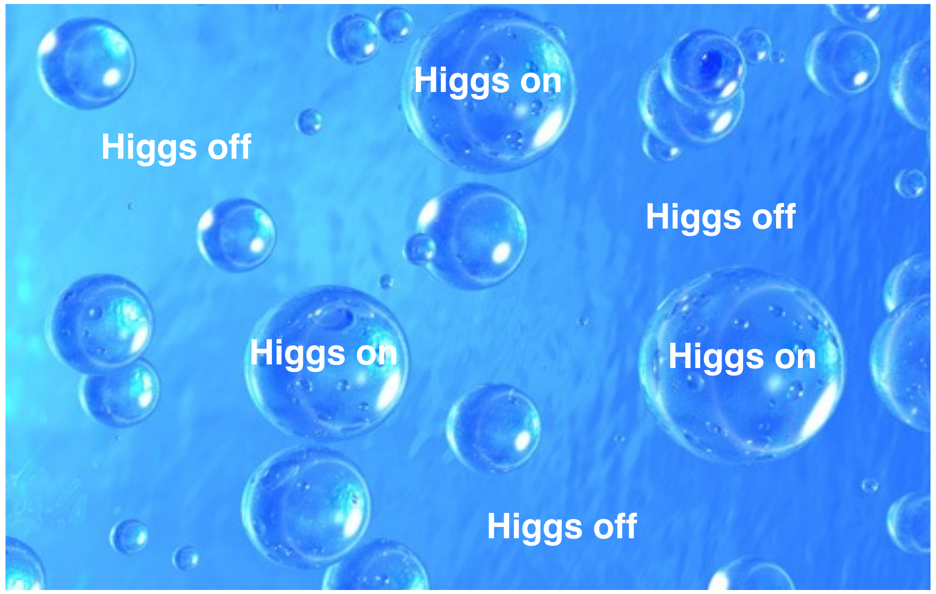
Information can be obtained from the trilinear and quartic Higgs self-couplings, which will be a main focus of the experimental and theoretical activities in particle physics during the coming years

The Higgs potential and the electroweak phase transition (EWPT)

[D. Gorbunov, V. Rubakov]

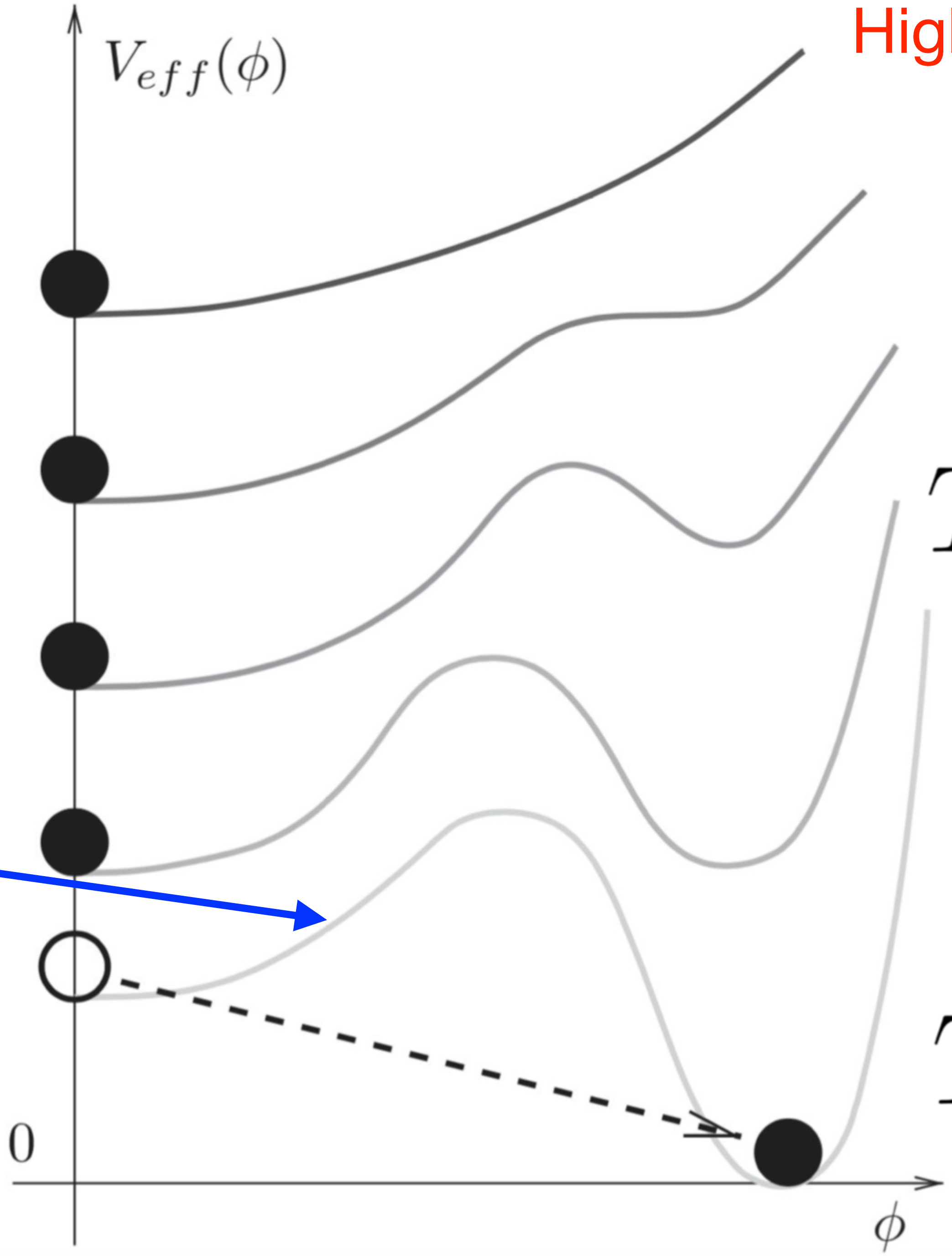
Temperature evolution of the Higgs potential in the early universe:

$$V(\phi, T) = V_0(\phi) + V^{loop}(\phi, T)$$



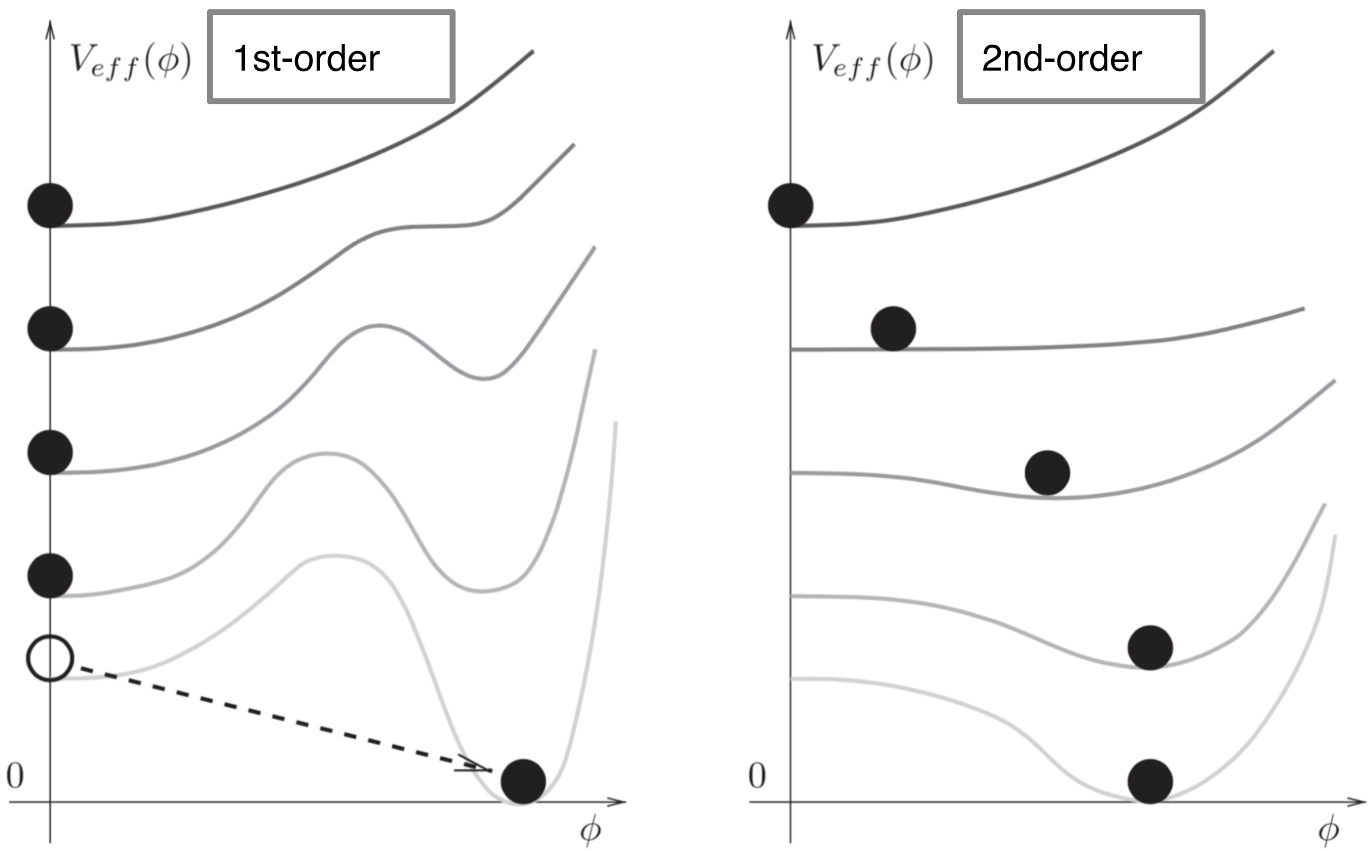
Potential barrier depends on trilinear Higgs coupling(s)

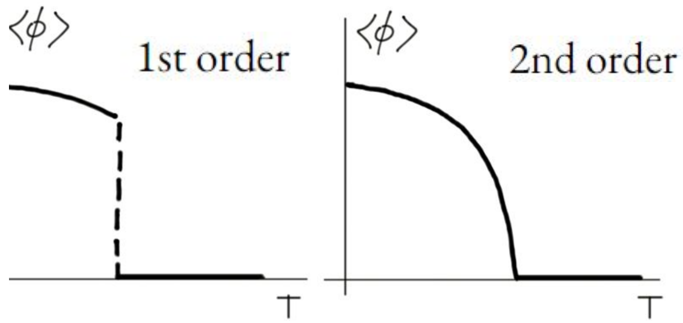
Baryogenesis: creation of the asymmetry between matter and antimatter in the universe requires strong first-order EWPT

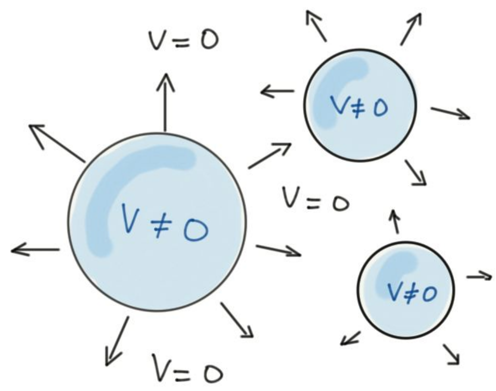


First-order vs. second order EWPT

[D. Gorbunov, V. Rubakov]







[K. Radchenko '23]

Potential barrier needed for first-order EWPT, depends on trilinear Higgs coupling(s)

Deviation of trilinear Higgs coupling from SM value is a typical feature of a strong first-order EWPT

Strongly first-order EWPT in the 2HDM

Barrier is related to a cubic term in the effective potential

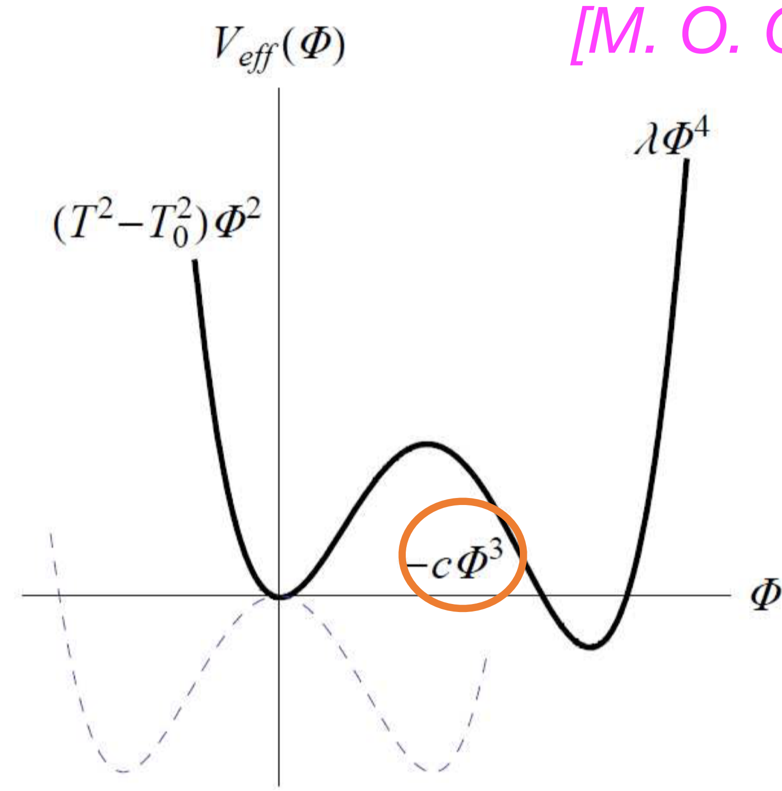
Arises from higher-order contributions and thermal corrections to the potential, in particular:

$$-\frac{T}{12\pi}\left[\mu_S^2 + \lambda_{HS} h^2 + \Pi_S\right]^{3/2}$$

⇒ For sizeable quartic couplings an effective cubic term in the Higgs potential is generated

[M. O. Olea '23]

⇒ Yields mass splitting between the BSM Higgs bosons and sizeable corrections to the trilinear Higgs coupling



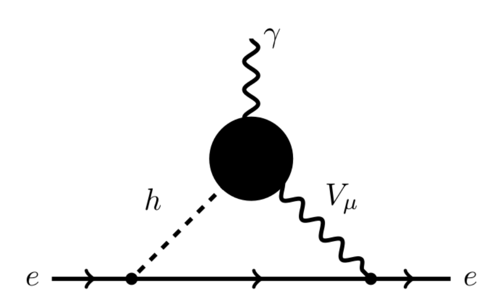
EWPT: are there additional sources for CP violation in the Higgs sector?

Baryogenesis: creation of the asymmetry between matter and anti-matter in the universe requires a strong first-order electroweak phase transition (EWPT)

First-order EWPT does not work in the SM
The amount of CP violation in the SM (induced by the CKM phase) is not sufficient to explain the observed asymmetry between matter and anti-matter in the universe

First-order EWPT can be realised in extended Higgs sectors
could give rise to detectable gravitational wave signal

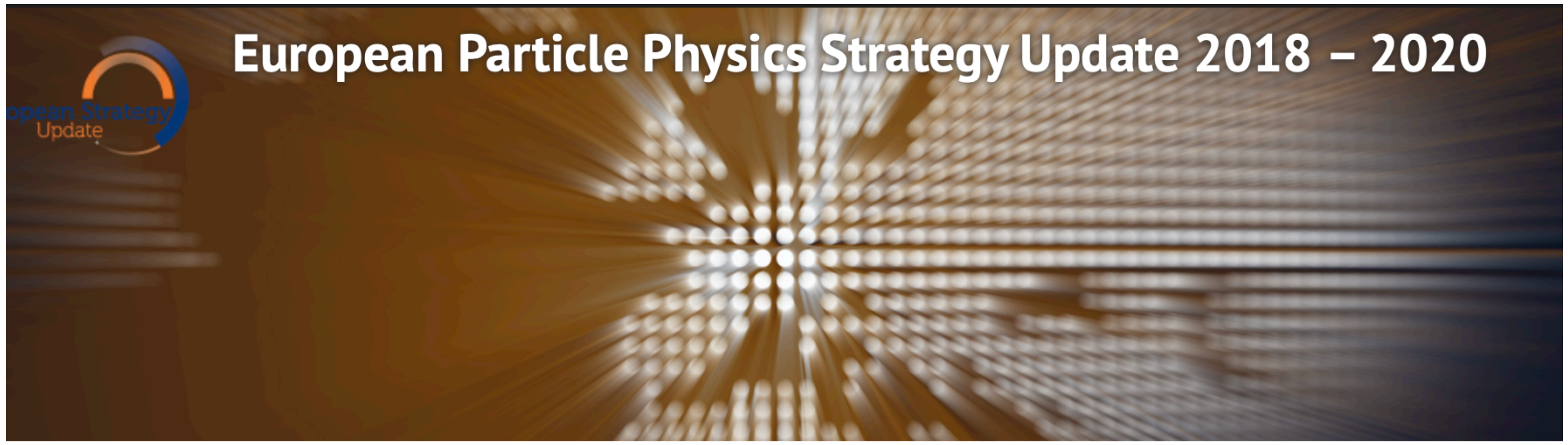
⇒ Search for additional sources of CP violation



Two-loop "Barr-Zee" electron EDM contribution

But: strong experimental constraints from limits on electric dipole moments (EDMs)

Latest update of European Strategy for Particle Physics



Future Projects:

3. High-priority future initiatives

a) An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

- *the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;*
- *Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.*

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

e⁺e⁻ Higgs factories

Linear

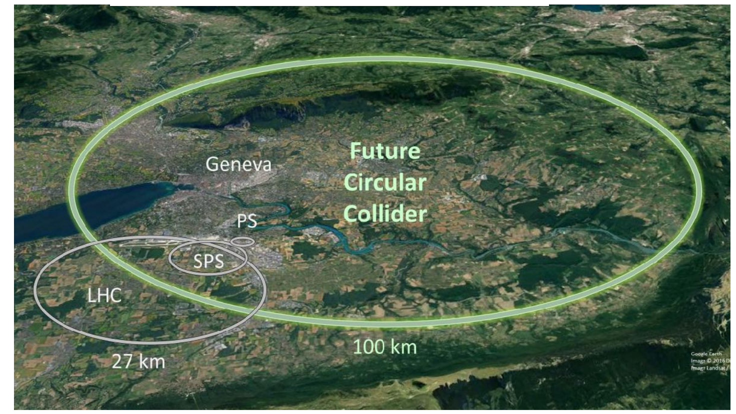
International **L**inear **C**ollider

ILC
Japan

Circular

Future **C**ircular **C**ollider

FCC-ee
CERN

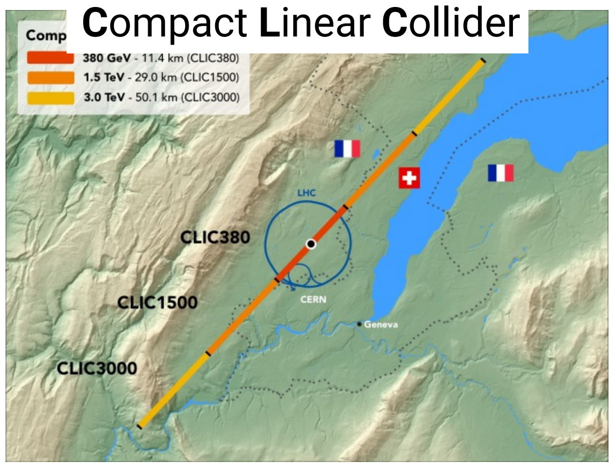


High-level differences:

- Energy reach
- Luminosity

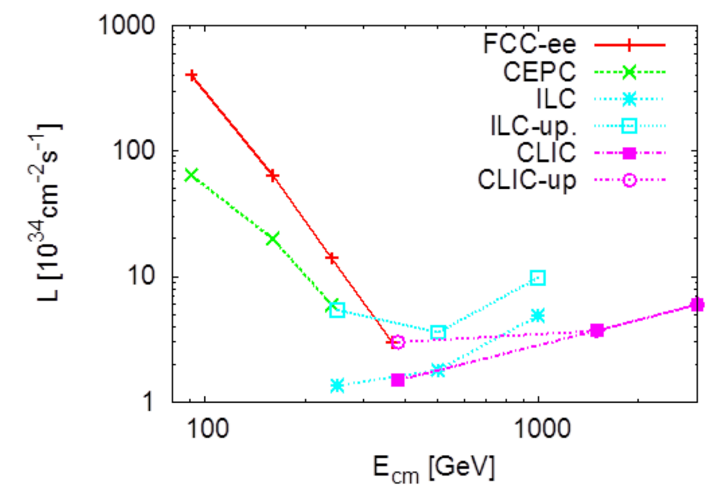
Compact **L**inear **C**ollider

CLIC
CERN

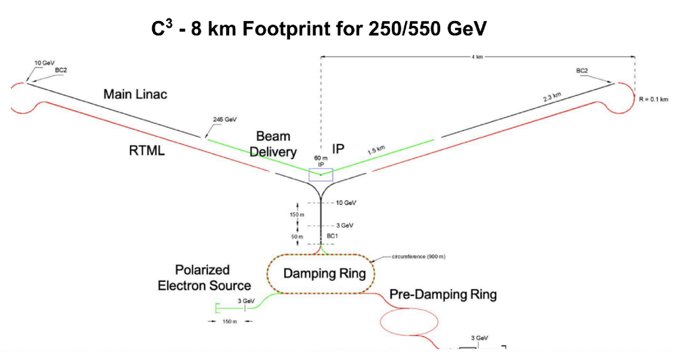


Circular **E**lectron **P**ositron **C**ollider

CEPC
China



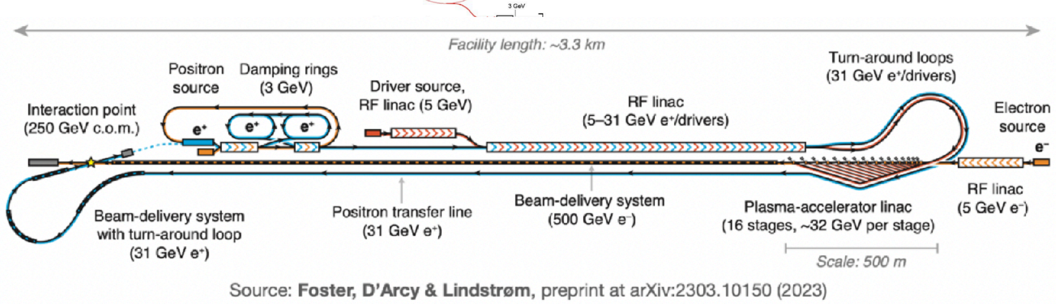
CCC



- 250 GeV — *ZH* threshold
- 350 GeV — *tt* threshold
- 550 GeV — *HHH* coupling
- ca. 1.5 TeV technology limit

- Based on superconducting RF (liquid nitrogen)
- Proposed at SLAC; very compact machine

HALHF



- 250 GeV — *ZH* threshold
- 365 GeV — *tt* threshold
- 10-30 TeV ?? technology limit

- New idea: e^- plasma acceleration, e^+ conventional LinAc
- ca. 10 years R&D needed to demonstrate feasibility
- Extremely compact: 3-4 km size, suitable for national lab

e^+e^- Higgs factories

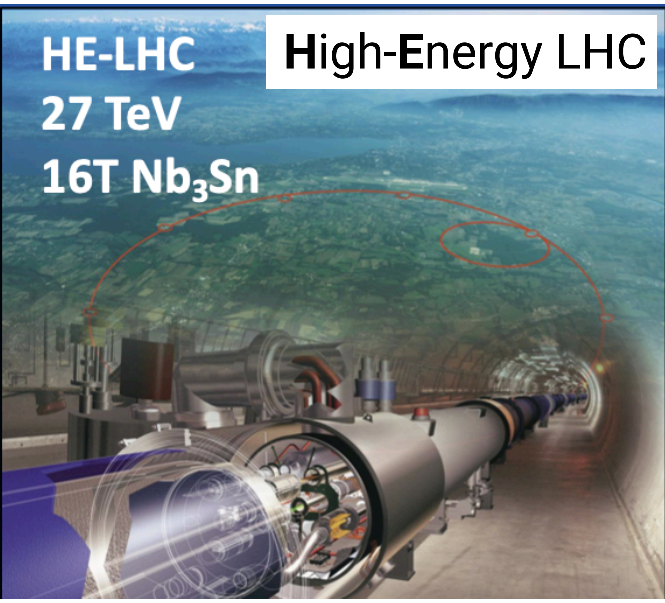
In the following I will discuss

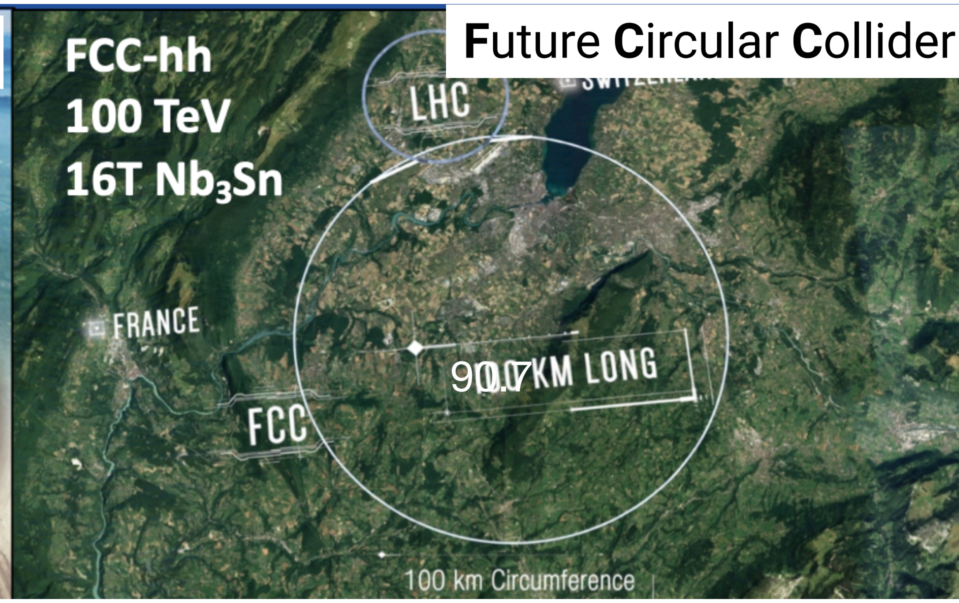
- a low-energy e^+e^- Higgs factory:
  c.m. energy up to 240 or 350 GeV, linear or circular

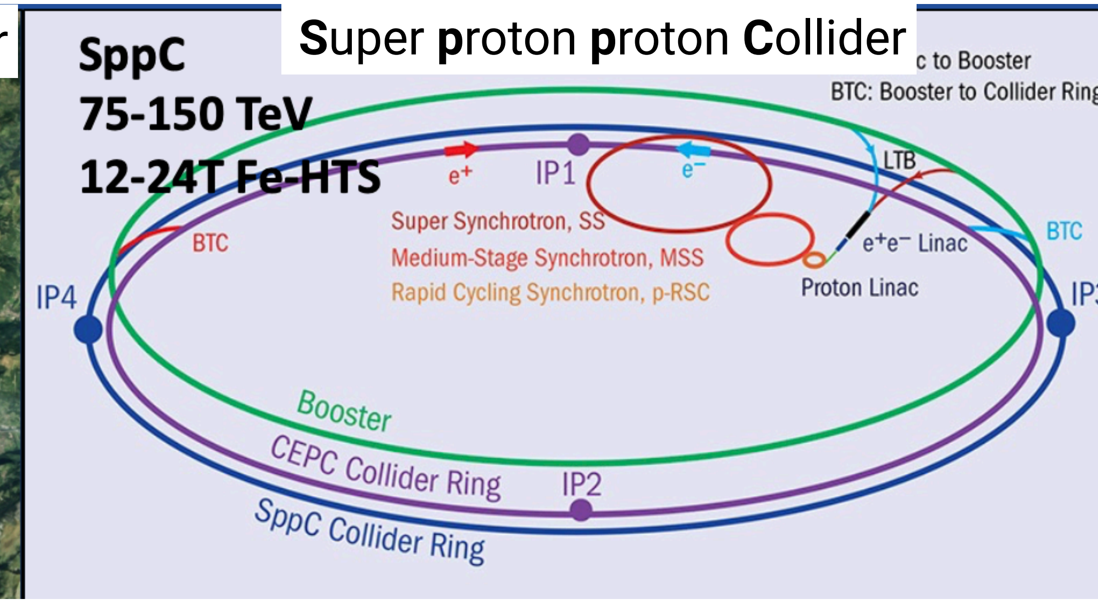
- e^+e^- Higgs factory extendable to high energy:
  c.m. energy up to 500 GeV or beyond, linear, direct measurement of trilinear Higgs self-coupling via ZHH production

Here: no specific discussion of muon collider capabilities (except for HHH production, see below) *[see talks by Dario and Patrick]*

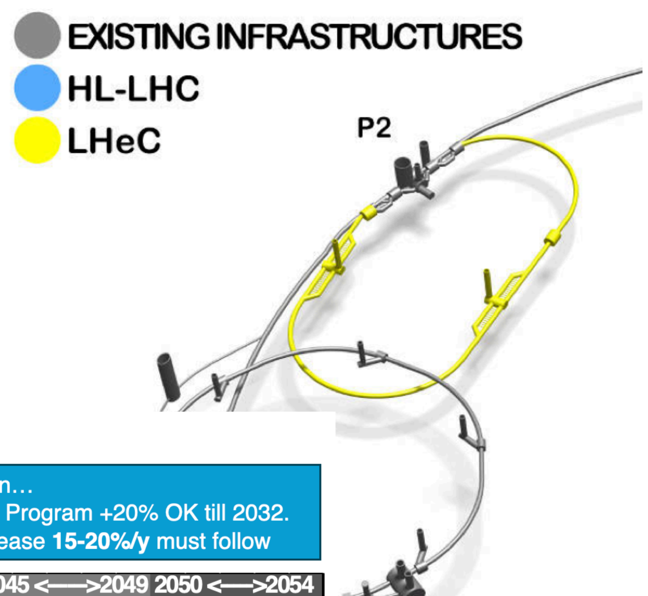
Future hadron colliders

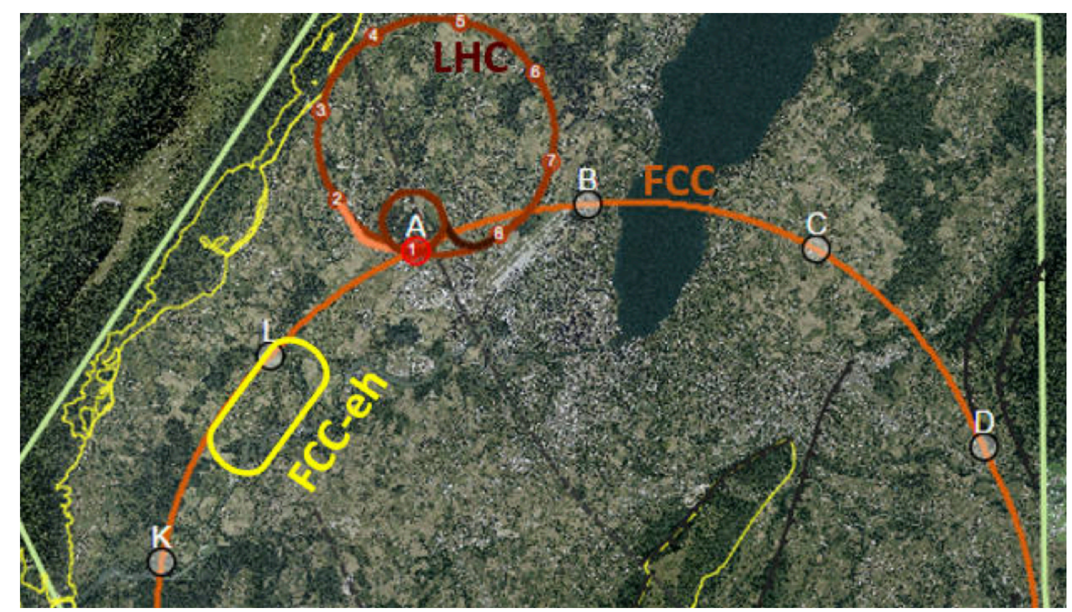


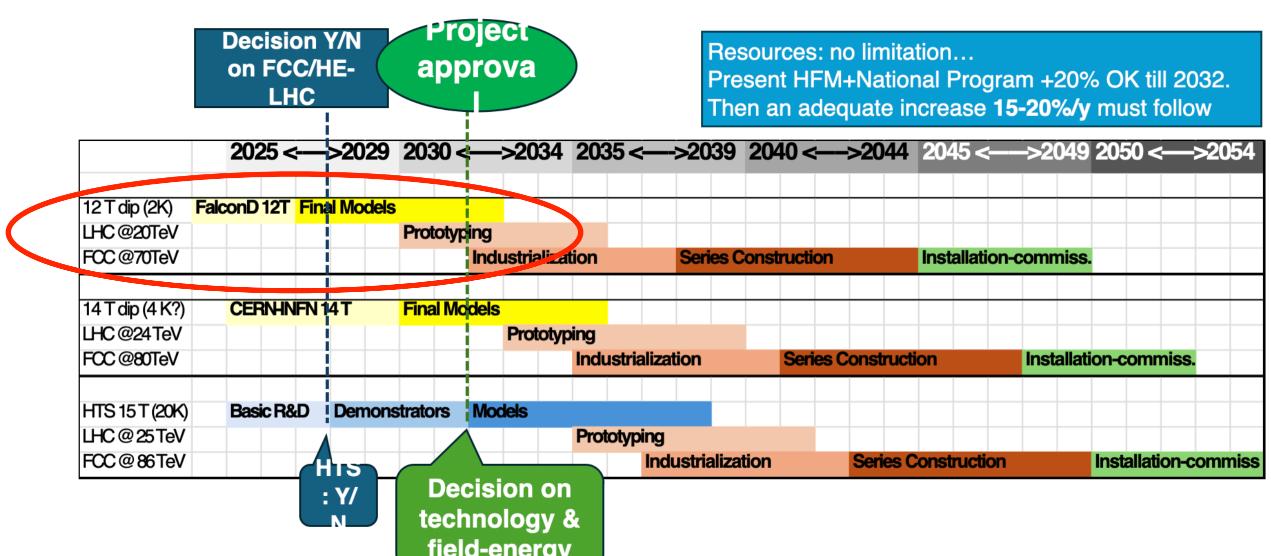




- The main challenge: high-field magnets: ~ 16+ T
- Electron-hadron collisions when combined with ERLs: LHeC, FCC-eh at CERN







[L. Rossi ’24]

Properties of the detected Higgs boson at 125 GeV

- Mass
- Spin and CP properties
- Couplings, partial widths, total width, branching ratios, production cross sections (total and differential), information from off-shell contributions, interference effects, …

~12 years after the discovery of the Higgs boson at 125 GeV (h125): high-precision measurement of the mass, detailed investigations of inclusive and differential rates

Mass at e^+e^- Higgs factory: O(10 MeV) accuracy possible

Higgs coupling determination at the LHC

Problem: no absolute measurement of total production cross section (no recoil method like LEP, ILC: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$)

Production $\times$ decay at the LHC yields combinations of Higgs couplings ($\Gamma_{\text{prod, decay}} \sim g^2_{\text{prod, decay}}$):

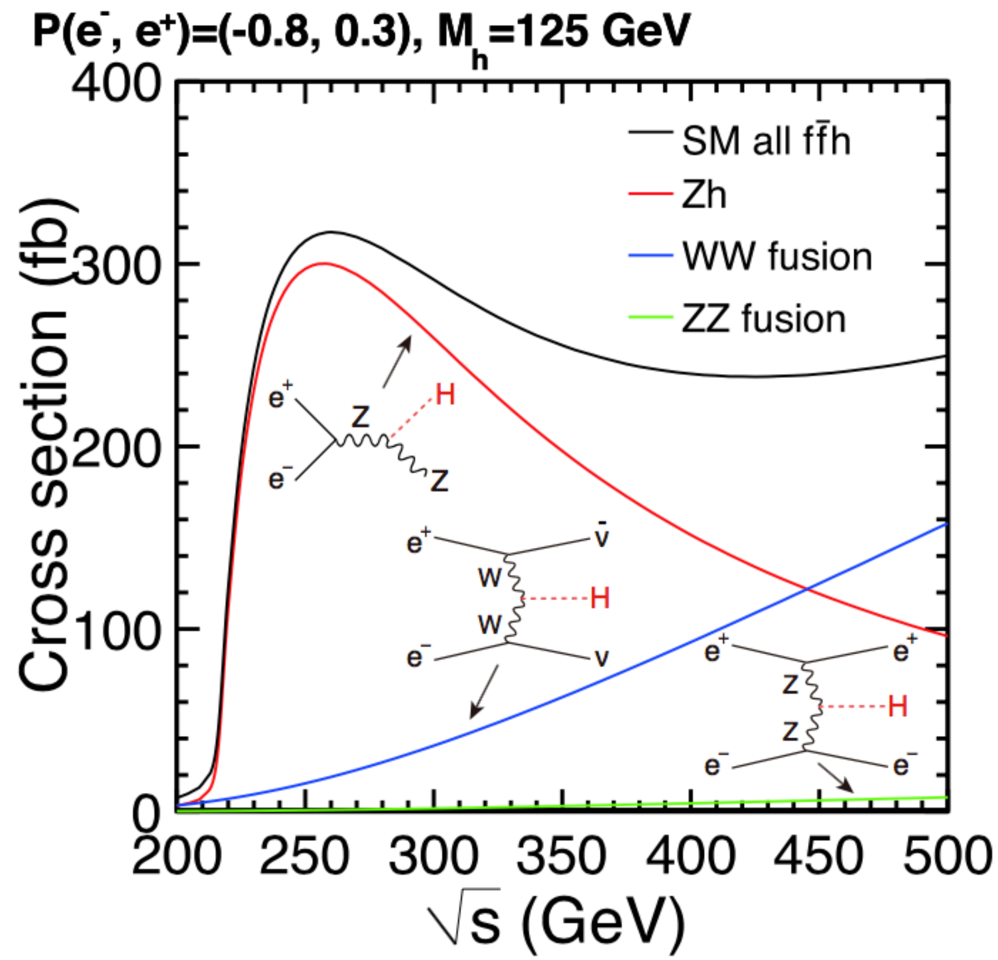
$$\sigma(H) \times \text{BR}(H \to a + b) \sim \frac{\Gamma_{\text{prod}} \Gamma_{\text{decay}}}{\Gamma_{\text{tot}}},$$

Total Higgs width cannot be determined without further assumptions

$\Rightarrow$ LHC can directly determine only ratios of couplings, e.g. $g^2_{H\tau\tau}/g^2_{HWW}$

Qualitative new feature at an e^+e^- Higgs factory

"Golden channel", $e^+e^- \longrightarrow ZH$, can best be exploited at 250 GeV

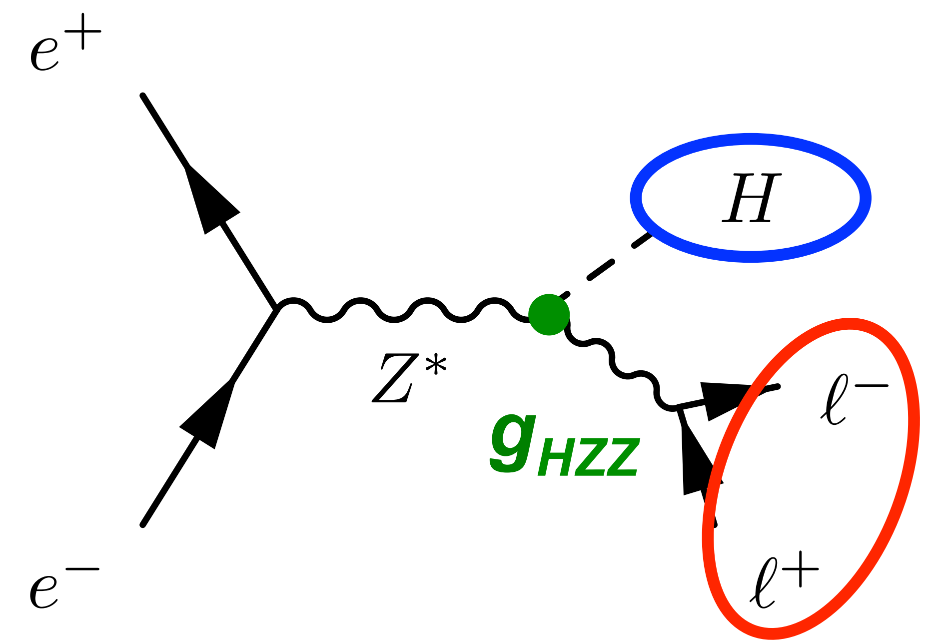


With this channel it is possible to detect the Higgs boson independently from the way it decays: "recoil method"
This leads to absolute and model-independent measurements of the Higgs production process and of the Higgs decay branching ratios

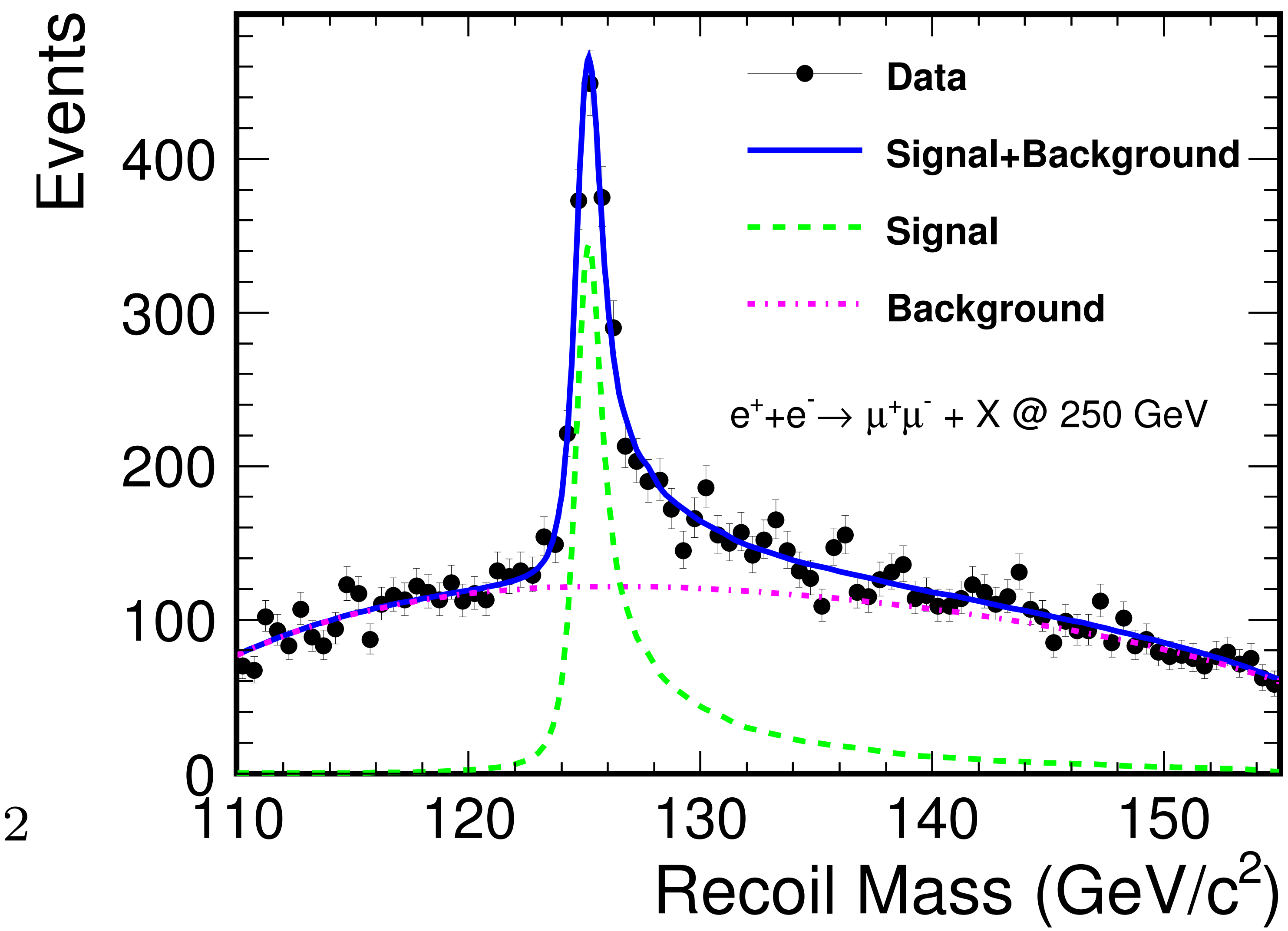
"Golden channel": $e^+e^- \to ZH, Z \to e^+e^-, \mu^+\mu^-$

Recoil method: detecting the Higgs boson without using its decay!

Reconstruct **Z→l⁺l⁻**
independent of Higgs decay
sensitive to invisible Higgs decays



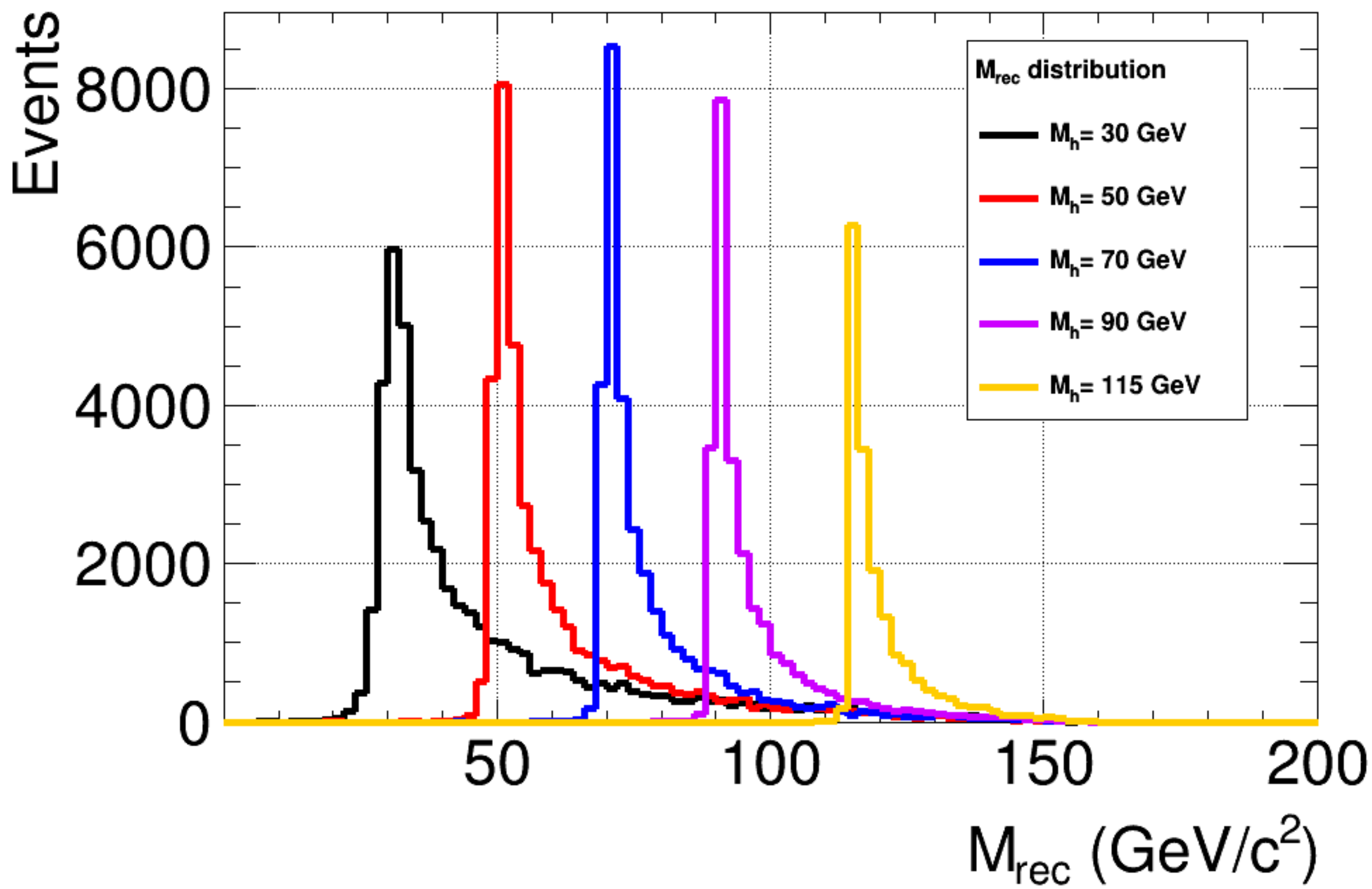
$$m^2_{\rm recoil} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$

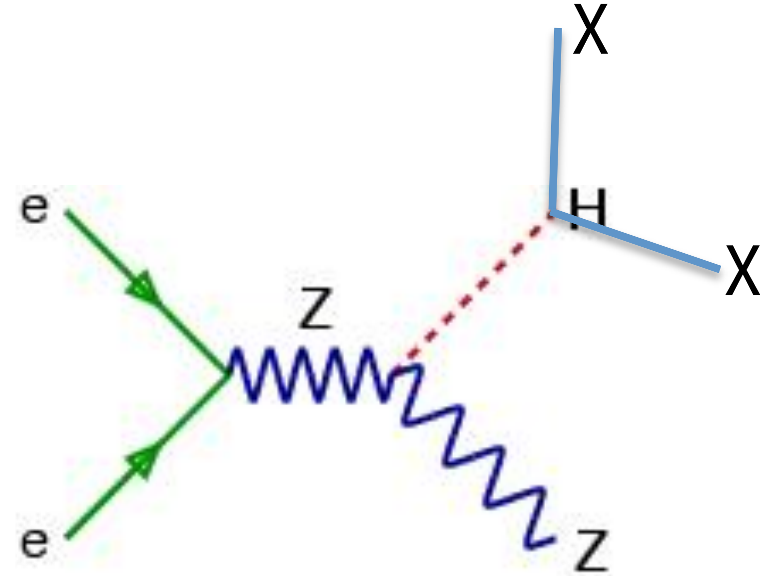


Since the Z ⟶ l⁺l⁻ decay branching fraction is known from the e⁺e⁻ collider LEP, this method yields an absolute measurement of the ZH cross section, the Higgs branching ratios and the Higgs width!

⇒ Large quantitative + qualitative improvements over HL-LHC

Invisible decays





⇒ Unique sensitivity at an e^+e^- Higgs factory!

Higgs couplings to fermions and gauge bosons: the quest for identifying the underlying physics

In many BSM models one expects only % level deviations or less from the SM couplings for BSM particles in the TeV range. Example of 2HDM-type model in decoupling limit:

$$\frac{g_{hVV}}{g_{h_{\rm SM}VV}} \simeq 1 - 0.3\% \left(\frac{200\ \text{GeV}}{m_A}\right)^4$$

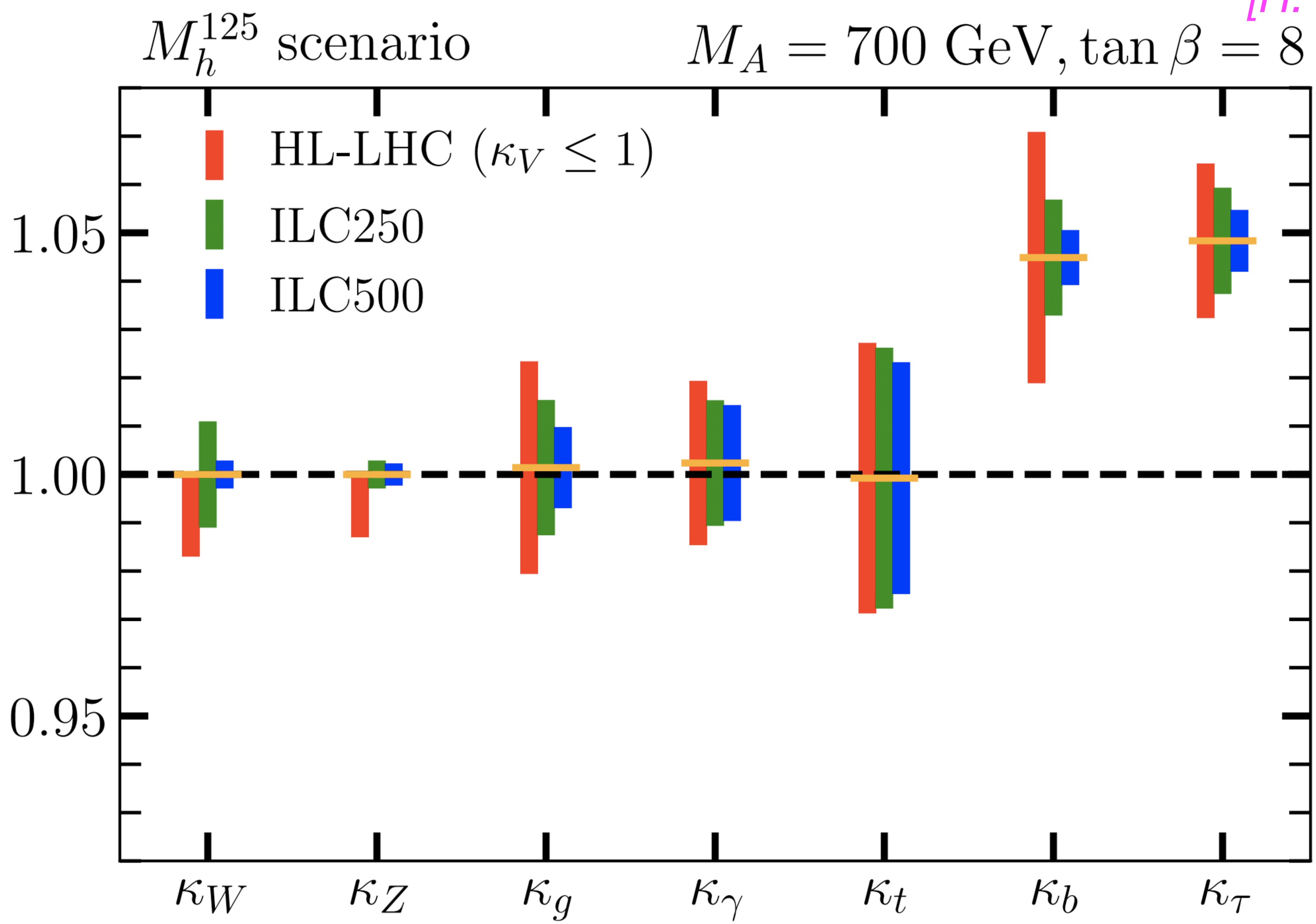
$$\frac{g_{htt}}{g_{h_{\rm SM}tt}} = \frac{g_{hcc}}{g_{h_{\rm SM}cc}} \simeq 1 - 1.7\% \left(\frac{200\ \text{GeV}}{m_A}\right)^2$$

$$\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} \simeq 1 + 40\% \left(\frac{200\ \text{GeV}}{m_A}\right)^2 .$$

⇒ Need very high precision for the couplings

Higgs couplings: example of "heavy" SUSY scenario

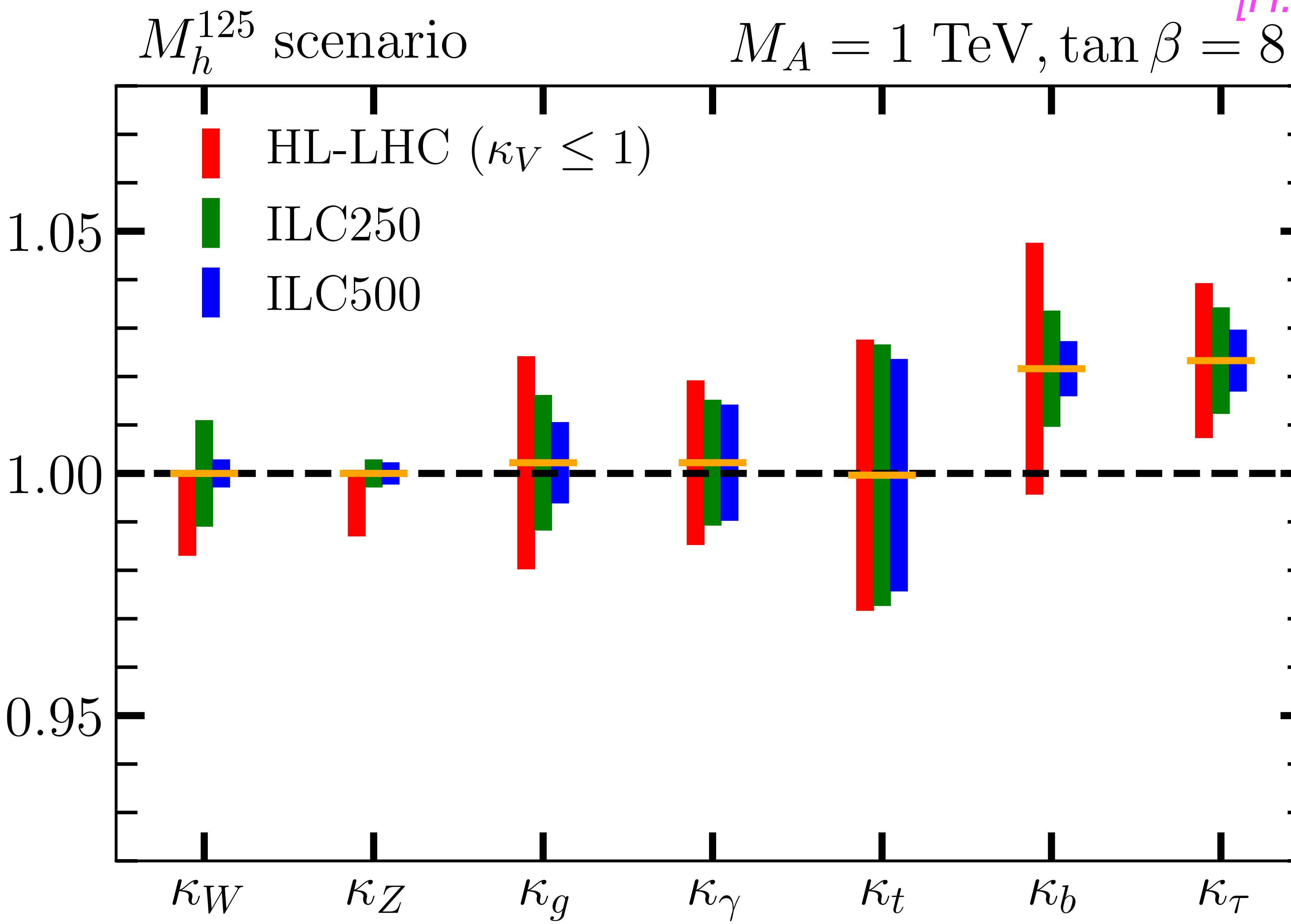
[H. Bahl et al. '20]



⇒ Need to resolve deviations at the level of 1% or below to get sensitivity to possible effects of BSM physics

Higgs couplings: example of “heavy” SUSY scenario

[H. Bahl et al. ’20]



⇒ Need to resolve deviations at the level of 1% or below to get sensitivity to possible effects of BSM physics

Higgs couplings: towards high precision

- A coupling is not a physical observable: if one talks about measuring Higgs couplings at the % level or better, one needs to precisely define what is actually meant by those couplings!

- For the determination of an appropriate coupling parameter at this level of accuracy the incorporation of strong and electroweak loop corrections is inevitable. This is in general not possible in a strictly model-independent way!

- For comparisons of present and future facilities it is crucial to clearly spell out under which assumptions these comparisons are done

``$\varkappa$ framework” and EFT approach for coupling analyses

Simplified framework for coupling analyses: deviations from SM parametrised by ``scale factors” $\varkappa_i$, where $\varkappa_i \equiv g_{Hii}/g^{SM,\,(0)}{}_{Hii}$

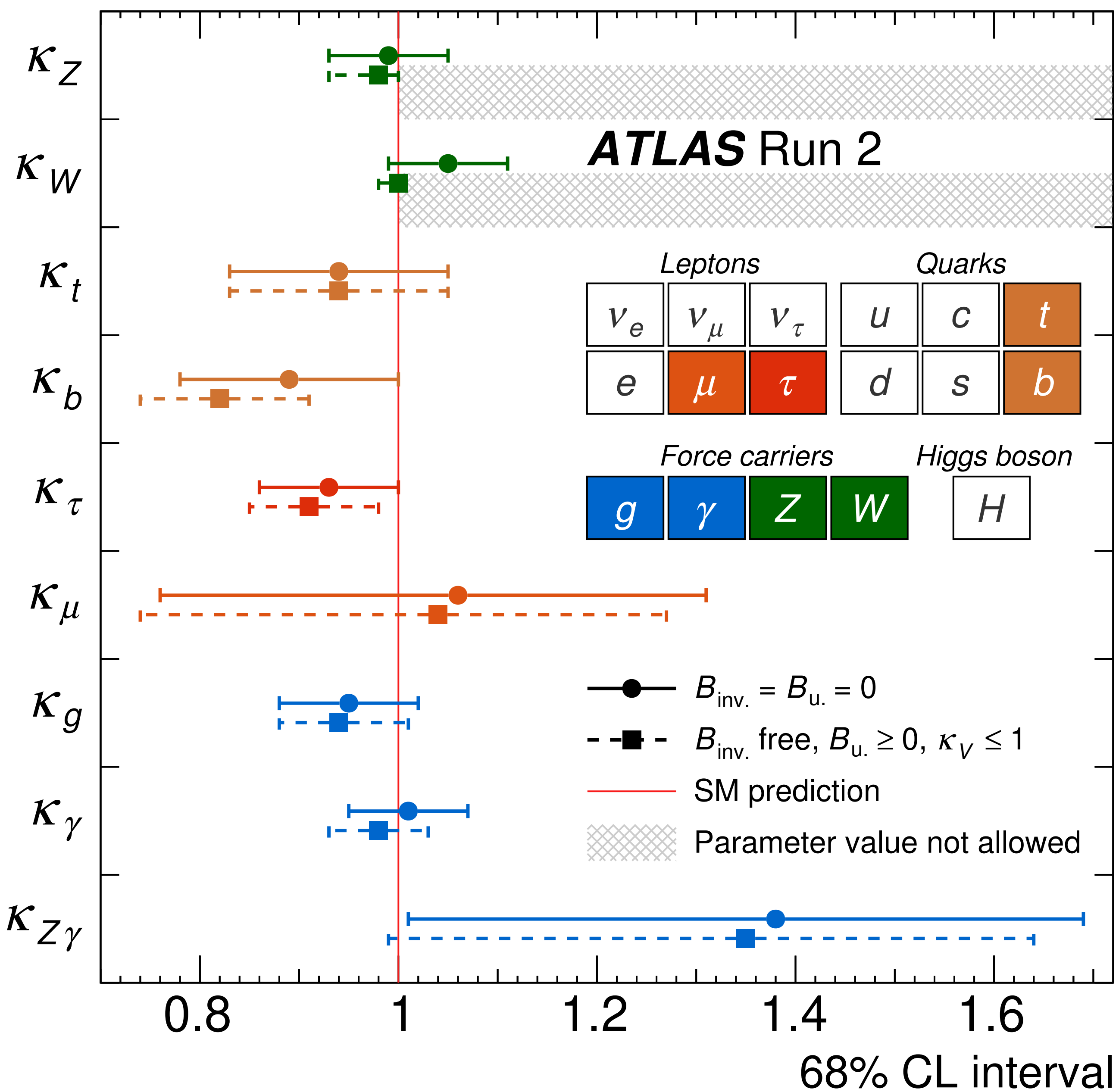
Assumptions inherent in the $\varkappa$ framework: signal corresponds to only one state, no overlapping resonances, etc., zero-width approximation, only modifications of coupling strengths (absolute values of the couplings) are considered
$\Rightarrow$ Assume that the observed state is a CP-even scalar

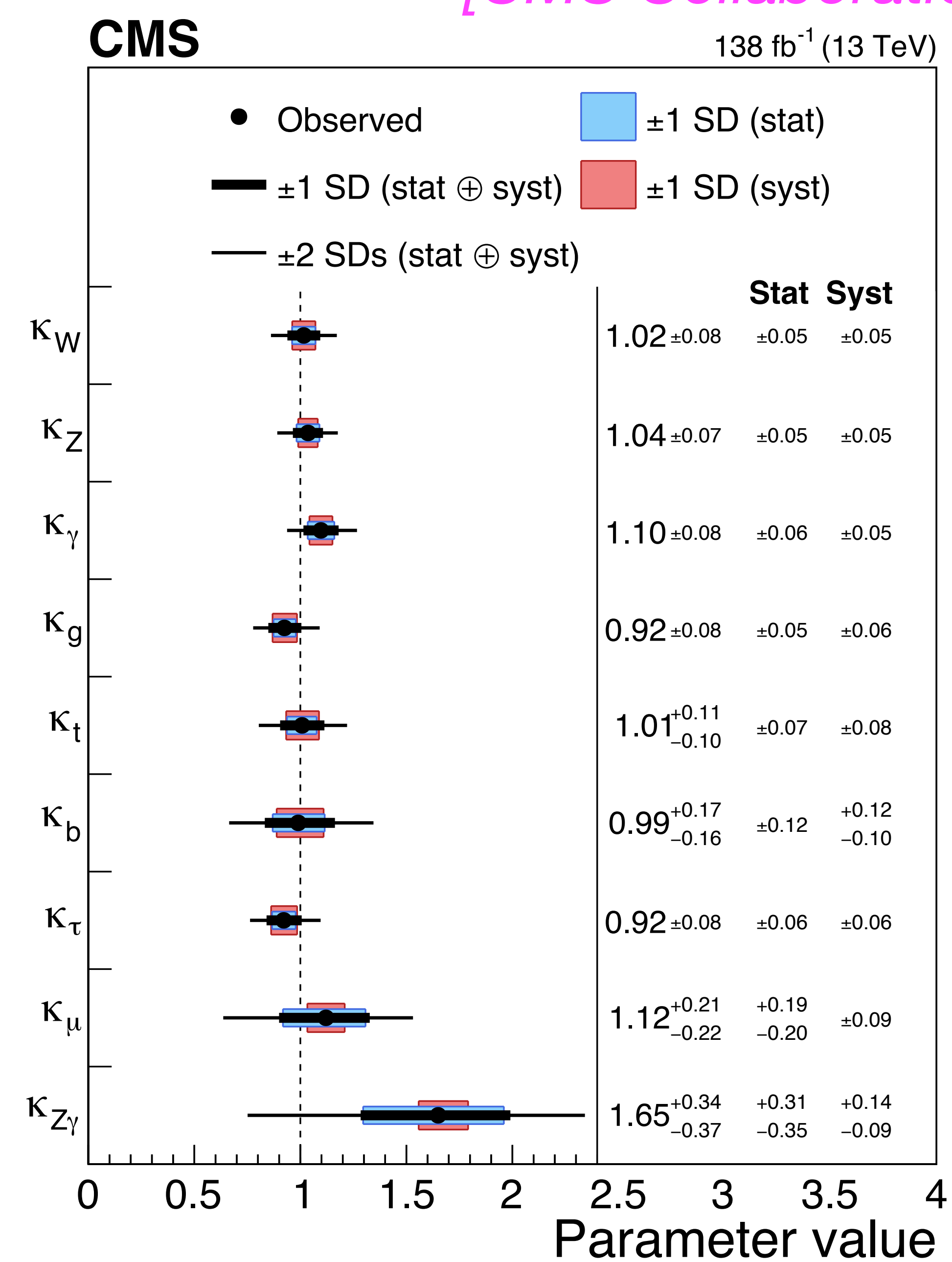
Theoretical assumptions in determination of the $\varkappa_i$:
$\varkappa_V \leqq 1$, no invisible / undetectable decay modes, …

EFT: fits for Wilson coefficients of higher-dimensional operators in SMEFT Lagrangian, …

Results for $\varkappa_i$

[ATLAS Collaboration ’22] *[CMS Collaboration ’22]*

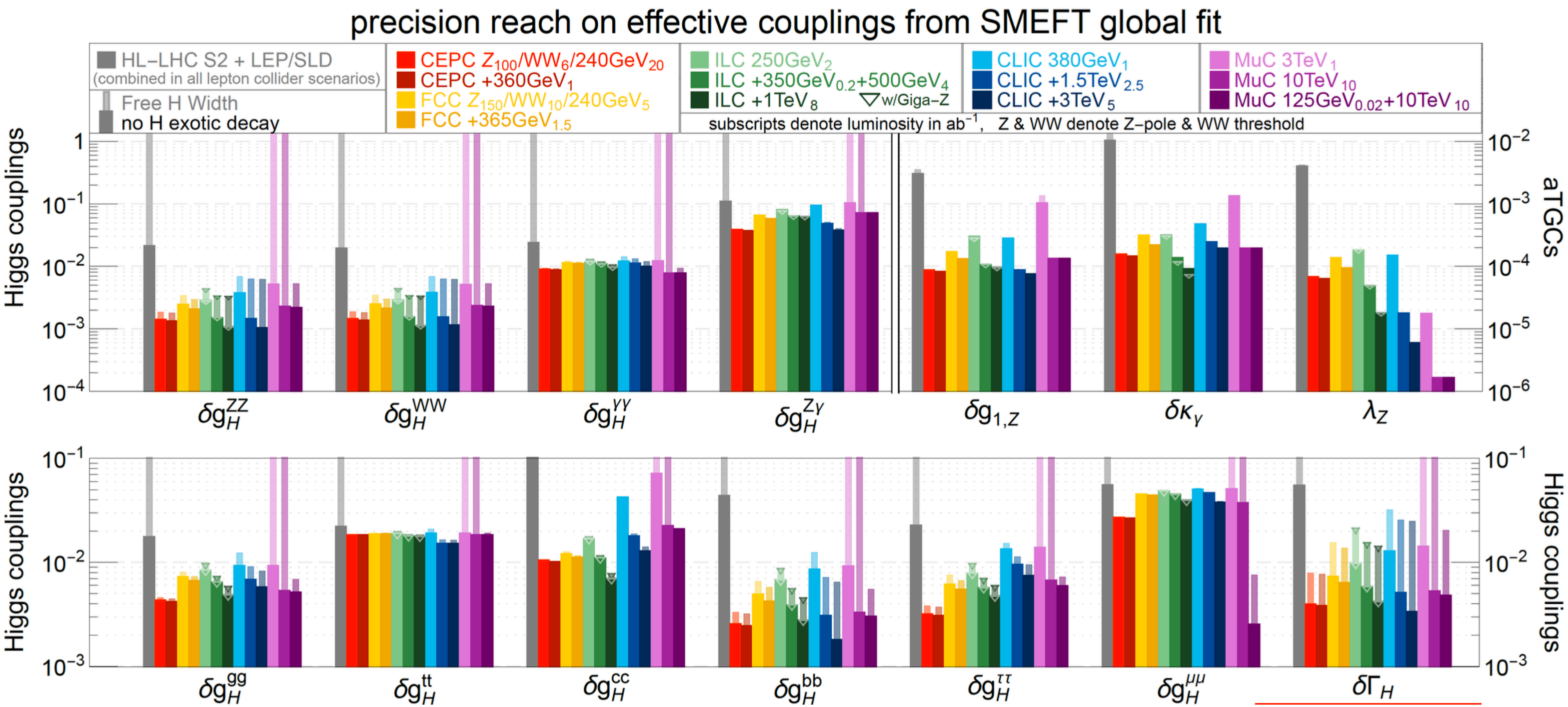




⇒ Precision of about 10% for several $\varkappa_i$

Global EFT fits: projections for future colliders

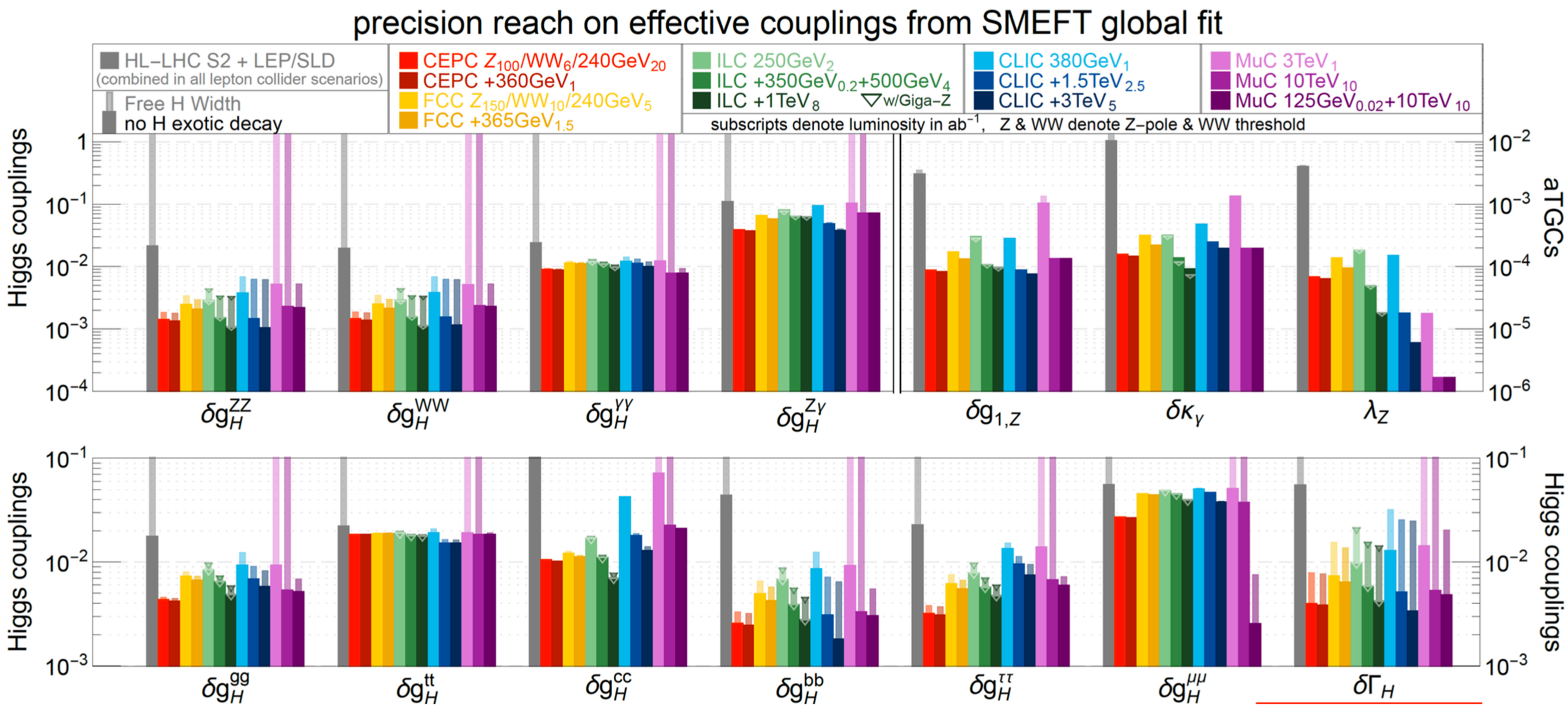
[J. de Blas et al. '22]



Global EFT fits: projections for future colliders

[J. Reuter '24]

- ☑ All Higgs factories perform similar: luminosity vs. polarization
- ☑ Couplings will be pushed to single percent-few per mille
- ☑ Gain at least one order of magnitude precision over HL-LHC
- ☑ If exotic Higgs decays exist: no absolute couplings from LHC



The quest for identifying the underlying physics

- What can we learn from the enhanced precision in comparison to the direct searches at the HL-LHC (existing limits and future prospects)?

- How significant will possible patterns of deviations be? How stringent are indirect hints for additional particles (typically scale like coupling/mass^2)?

- How well can one distinguish between different realisations of possible BSM physics?

Questions of this kind have hardly been touched upon at the previous update of the European Strategy for Particle Physics, but they are crucial for making the case for a (low-energy) e^+e^- Higgs factory in the wider scientific community!

CP properties of h125

$\mathcal{CP}$ properties: more difficult than spin, observed state can be any admixture of $\mathcal{CP}$-even and $\mathcal{CP}$-odd components

Observables mainly used for investigaton of $\mathcal{CP}$-properties ($H \to ZZ^*, WW^*$ and H production in weak boson fusion) involve HVV coupling

General structure of HVV coupling (from Lorentz invariance):

$$a_1(q_1, q_2) g^{\mu\nu} + a_2(q_1, q_2) \left[(q_1 q_2)\, g^{\mu\nu} - q_1^\mu q_2^\nu \right] + a_3(q_1, q_2) \epsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}$$

SM, pure $\mathcal{CP}$-even state: $a_1 = 1, a_2 = 0, a_3 = 0$,

Pure $\mathcal{CP}$-odd state: $a_1 = 0, a_2 = 0, a_3 = 1$

However: in many models (example: SUSY, 2HDM, ...) a_3 is loop-induced and heavily suppressed

Sensitivity at the LHC and e+e− Higgs factories

[C. Li, G. Moortgat-Pick '24]

$e^+e^- \to HZ \to H\mu^-\mu^+$ with transverse and longitudinal beam pol.

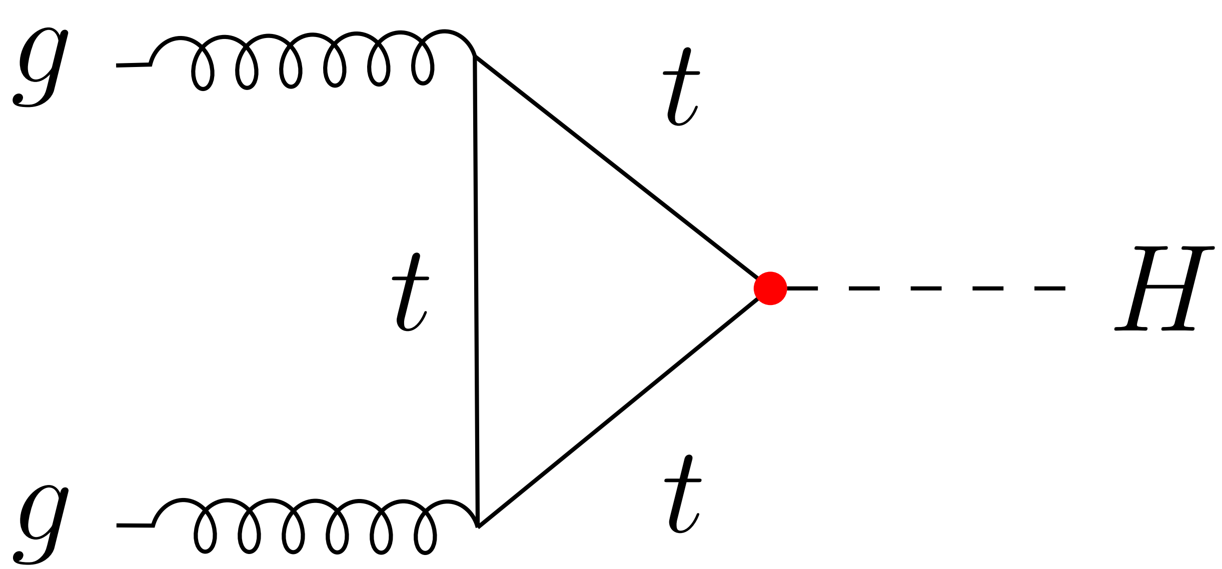
Experiments	ATLAS[24]	CMS[19]	HL-LHC[25]	CEPC[29]	CLIC[30]	CLIC [31, 40]	ILC
Processes	$H \to 4\ell$	$H \to 4\ell$	$H \to 4\ell$	HZ	W-fusion	Z-fusion	$HZ,\ Z \to \mu^+\mu^-$
$\sqrt{s}$ [GeV]	13000	13000	14000	240	3000	1000	250
Luminosity [fb^{-1}]	139	137	3000	5600	5000	8000	5000
$(\lvert P_-\rvert, \lvert P_+\rvert)$							$(90\%, 40\%)$
$\tilde{c}_{HZZ}$ $(\times 10^{-2})$ 95% C.L. (2σ)limit	[-16.4, 24.0]	[-9.0, 7.0]	[-9.1, 9.1]	[-1.6, 1.6]	[-3.3, 3.3]	[-1.1, 1.1]	[-1.1, 1.0]

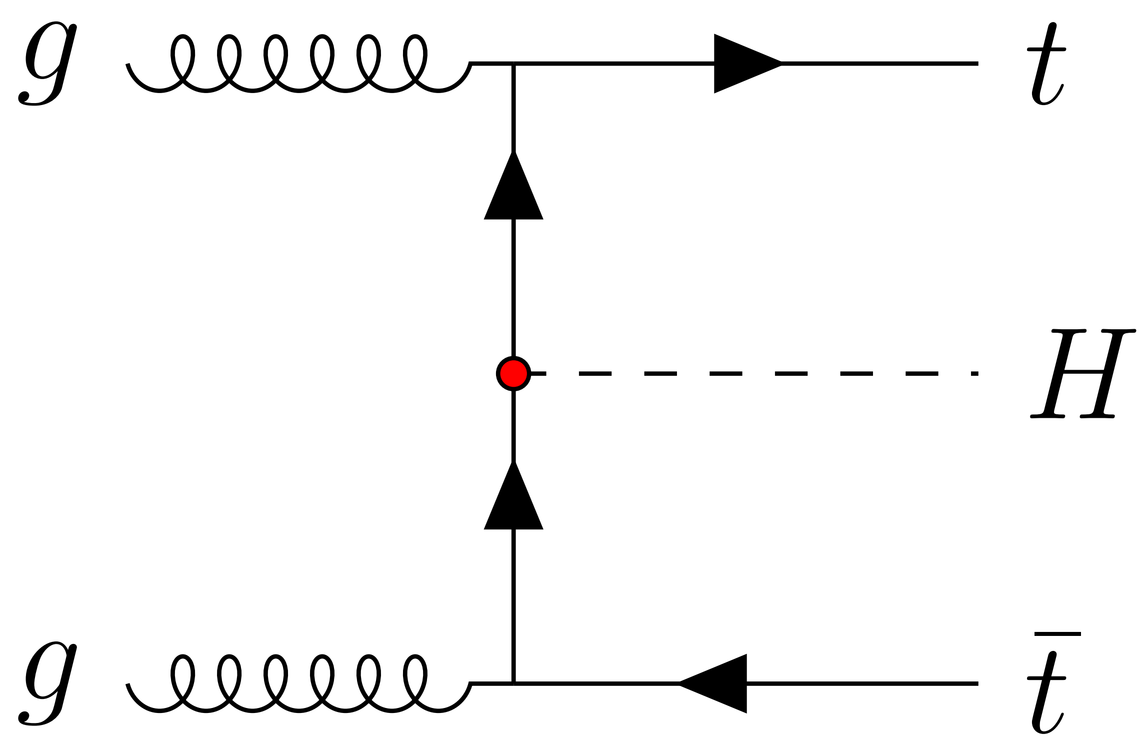
$\tilde{c}_{HZZ} = a_3$

CP properties of h125

It has been experimentally verified that h125 is not a pure CP-odd state, but it is by no means clear that it is a pure CP-even state

Sensitive tests via processes involving only Higgs couplings to fermions





with H → $\tau\tau$, bb, …

CP structure of the top Yukawa coupling: current constraints and HL-LHC prospects

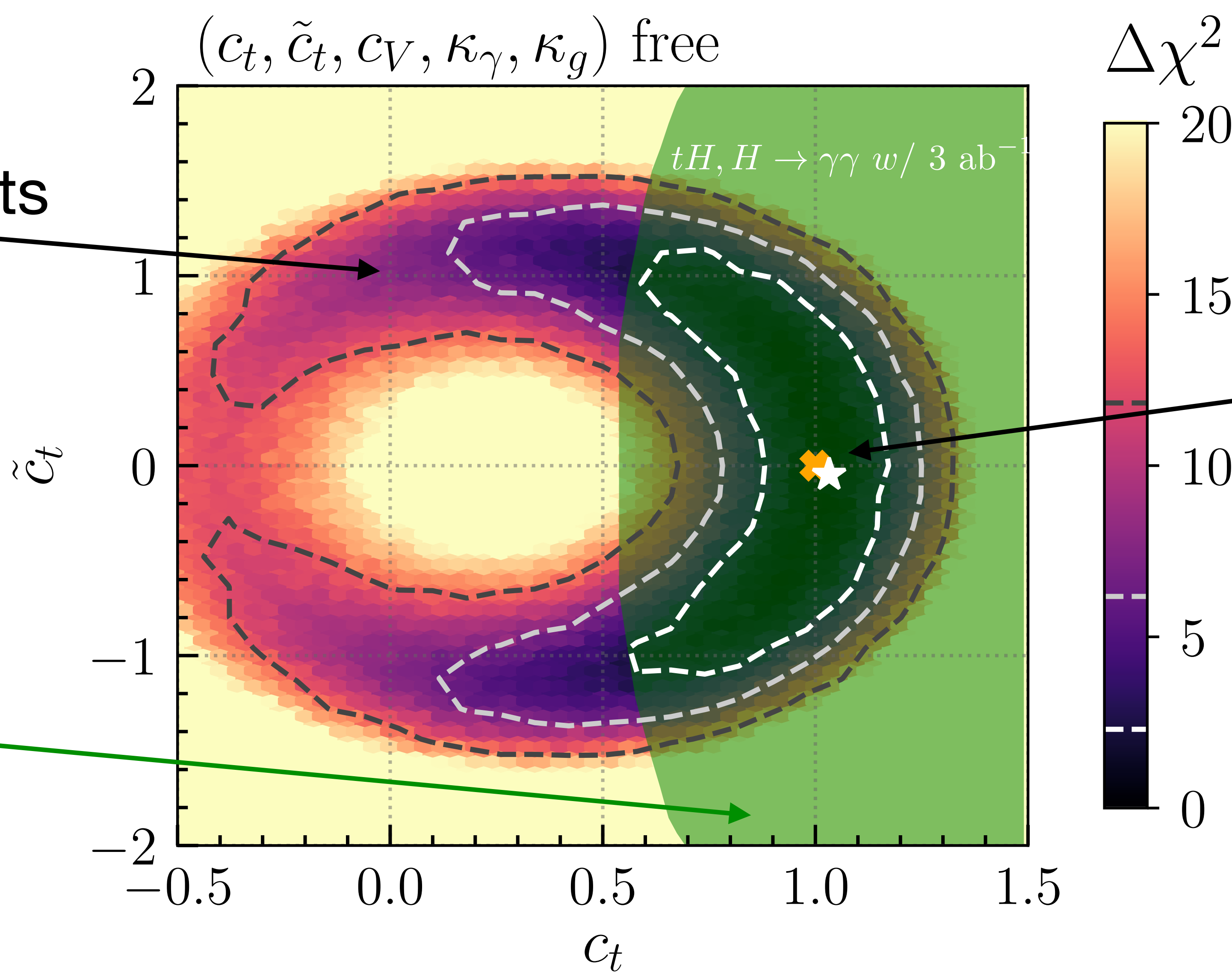
[H. Bahl et al. '20]

Global fit to LHC inclusive and differential signal rates

$$\mathcal{L}_{\rm yuk} = -\frac{y_t^{\rm SM}}{\sqrt{2}}\bar{t}\,(c_t + i\gamma_5\tilde{c}_t)\,tH$$

current constraints

impact of measurement of *tH* production at the HL-LHC



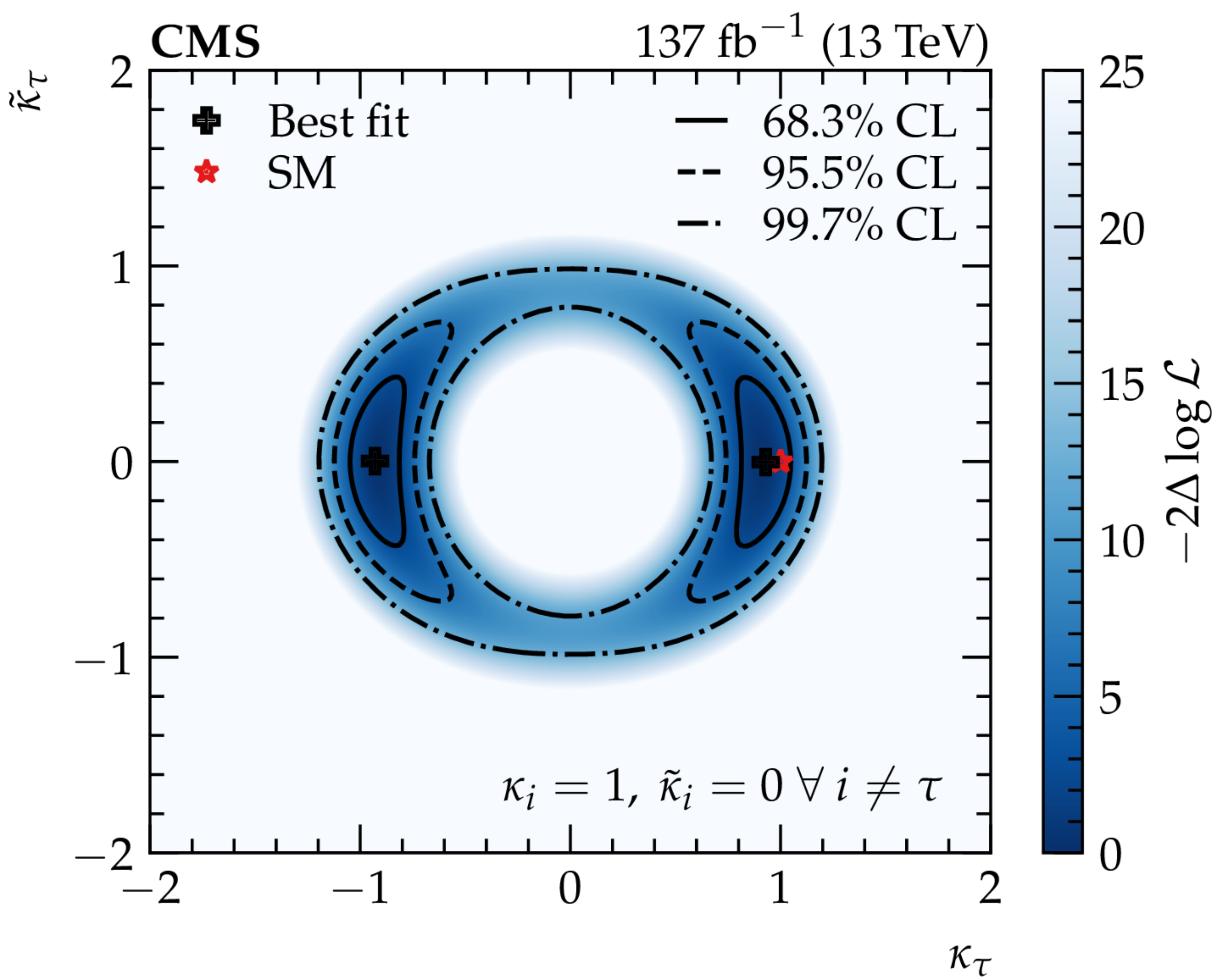
SM value

⇒ Only mild constraints on the CP structure at LHC and HL-LHC

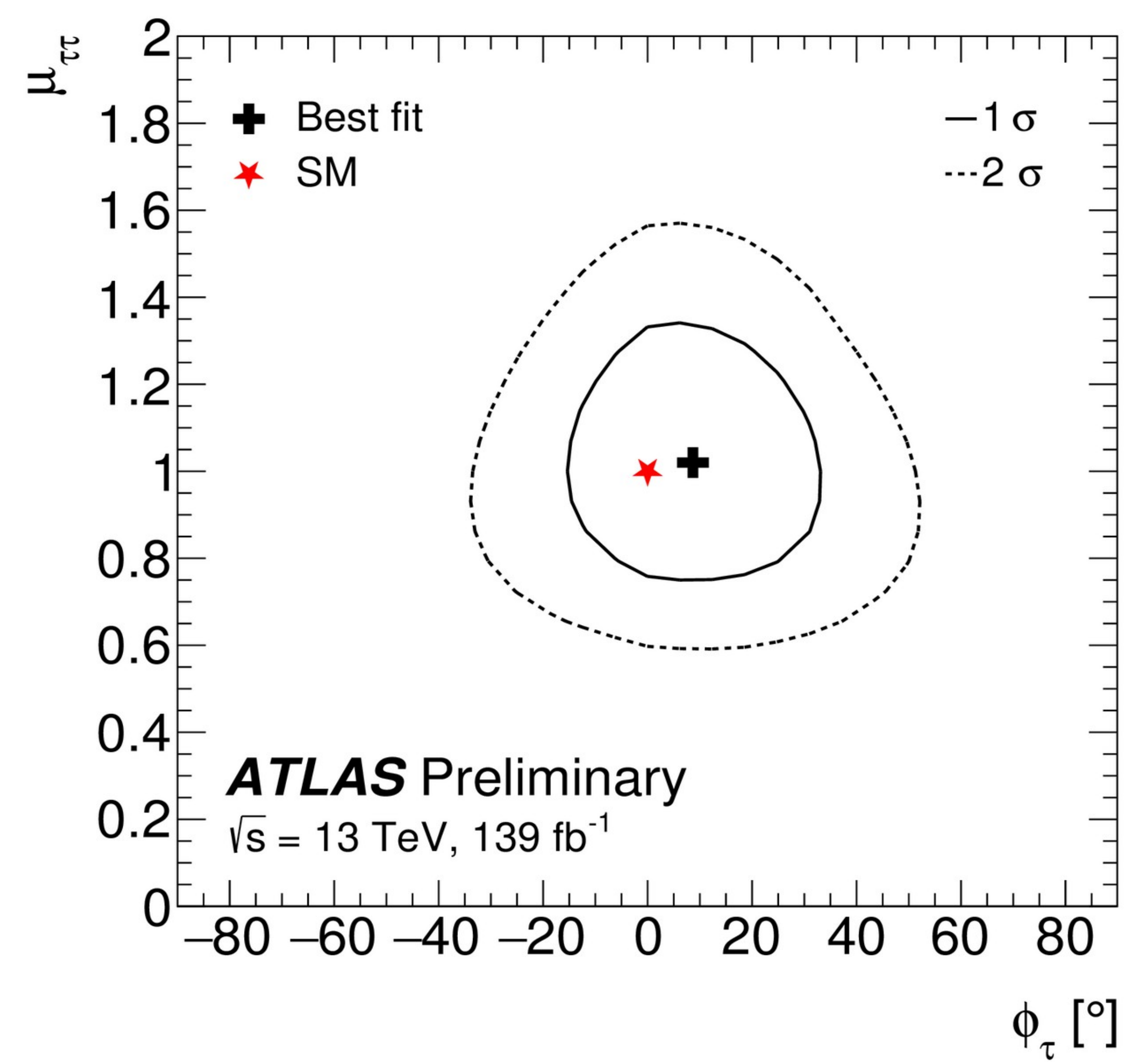
Test of CP violation in the tau Yukawa coupling

Constraints on the CP structure of the tau Yukawa coupling from h125 → **ττ** decays using angular correlation between decay products:

[CMS Collaboration '21]



[ATLAS Collaboration '22]



Effect on global CP analysis of Higgs-fermion couplings

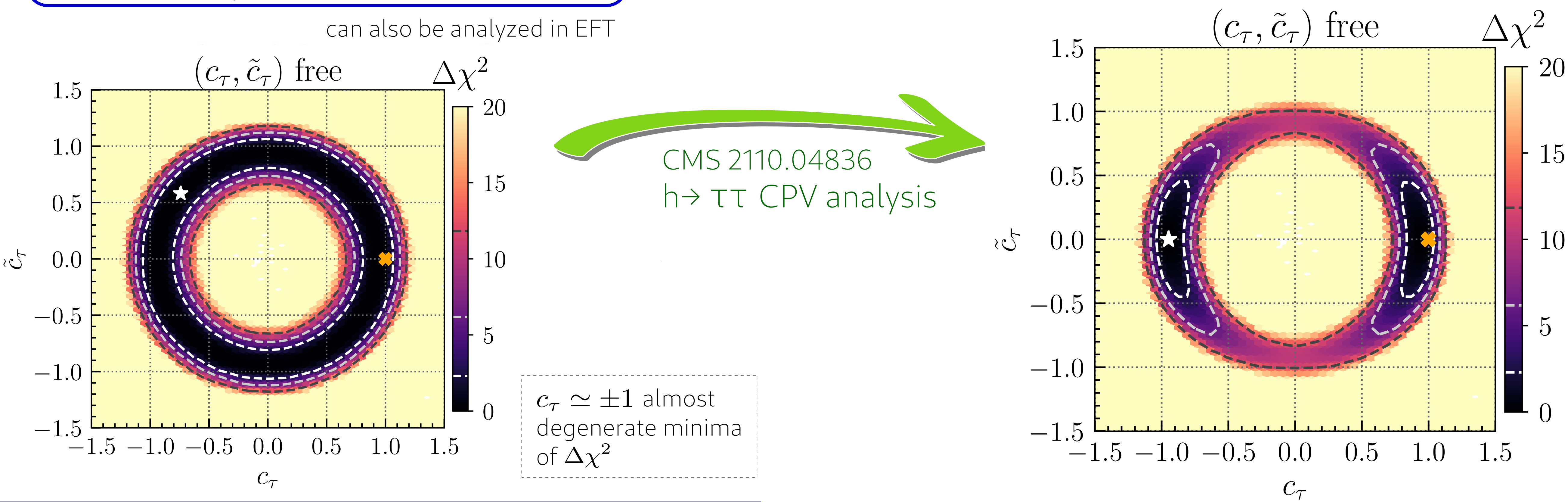
[H. Bahl et al. '22]

Incorporation of recent CMS result on the CP structure of the tau Yukawa coupling from h125 → **ττ** decays using angular correlation between the decay products

$$\mathcal{L}_{\text{Yuk}} = -\sum_f \frac{y_f}{\sqrt{2}} \bar{f} \left(c_f + i\gamma_5 \tilde{c}_f \right) f h,$$

can also be analyzed in EFT

Global fit using **HiggsSignals** + recent analyses



$c_\tau \simeq \pm 1$ almost degenerate minima of $\Delta\chi^2$

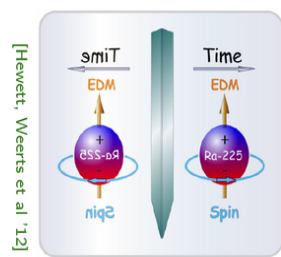
Ring-structure from upper/lower bound on BR

CMS analysis excludes large $\tilde{c}_\tau$

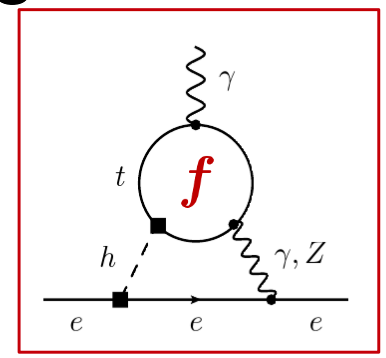
CP structure of the Higgs-fermion couplings

[H. Bahl et al. '22]

Comparison with the existing EDM constraints



EDM violates $\mathcal{T}$ and $\mathcal{P}$ $\Rightarrow \not{CP}$



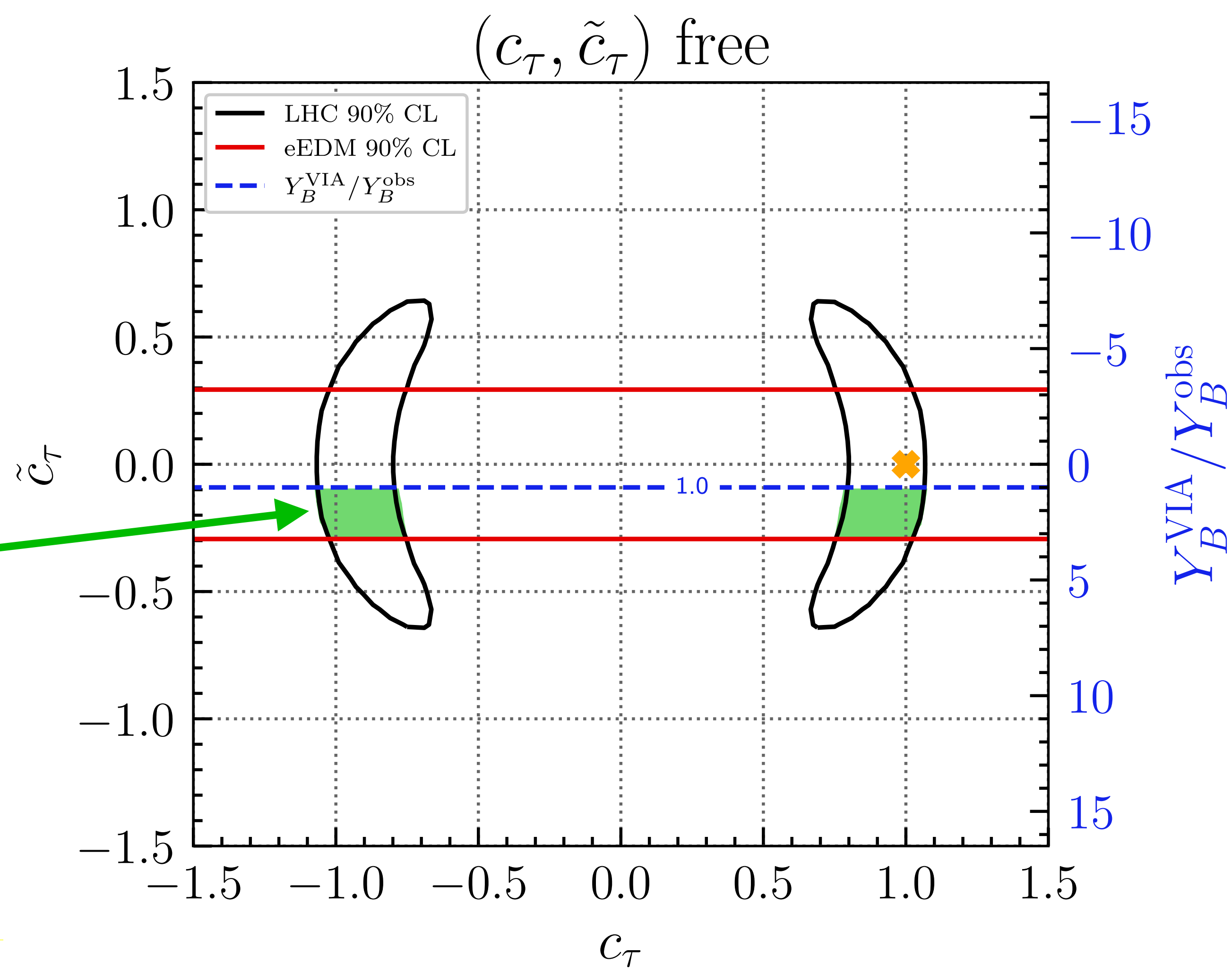
ACME [Nature '18]:

$$d_e \leq 1.1 \times 10^{-29}\, e\,\text{cm at } 90\%\text{ CL}$$

Using [Panico, Pomarol, Riembau '18], [Brod, Haisch, Zupan '13], [Brod, Stamou '18],...

Analysis of the resulting amount of baryon asymmetry in the Universe

Electron electric dipole moment $d_e \propto \tilde{c}_f$



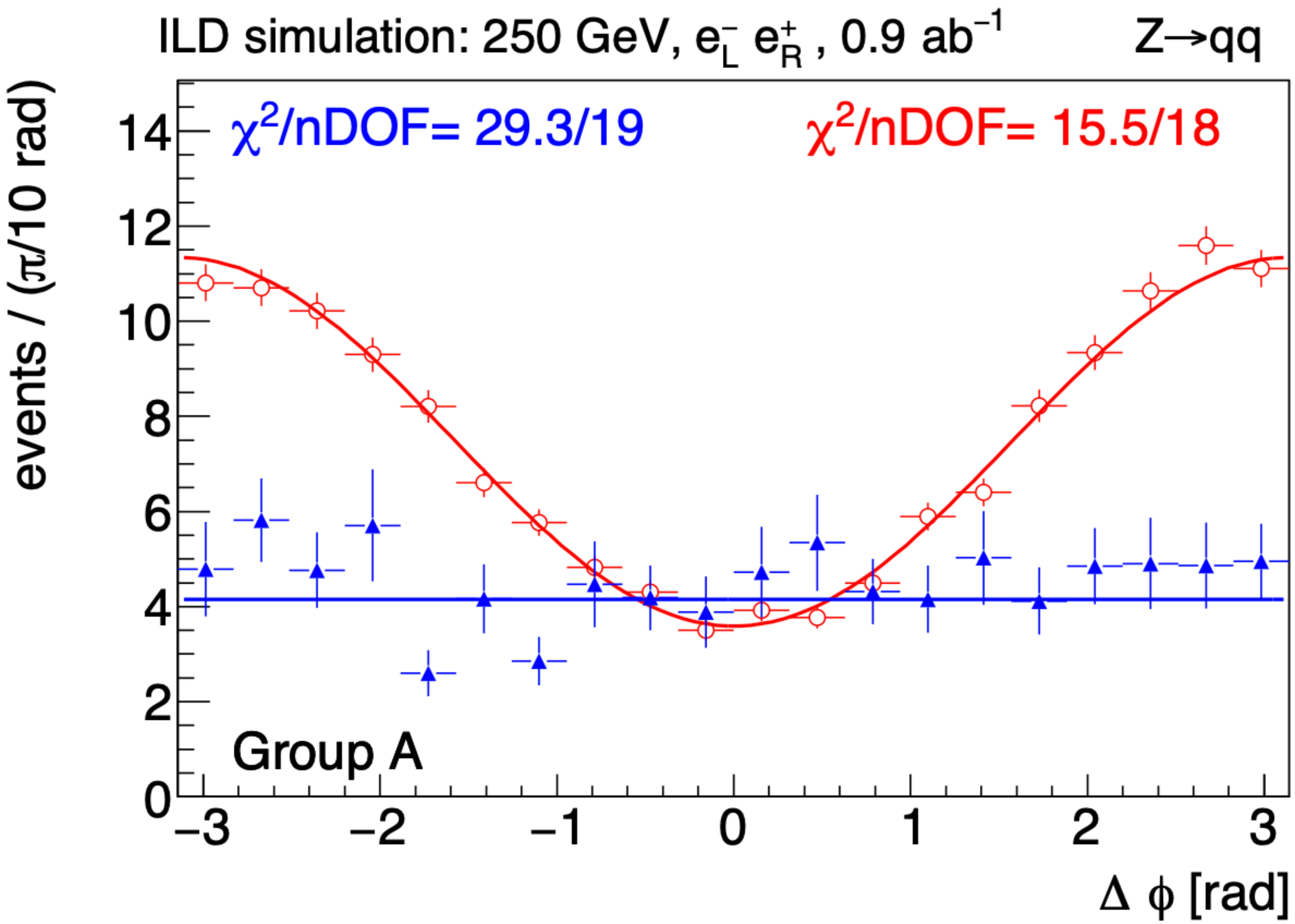
Allowed by LHC, EDM constraints and baryogenesis!

Could work even for the case where CP violation occurs just in the τ coupling (in optimistic scenario)!

$\Rightarrow$ CP violation in τ coupling could yield correct baryon asymmetry!

Higgs factory analysis

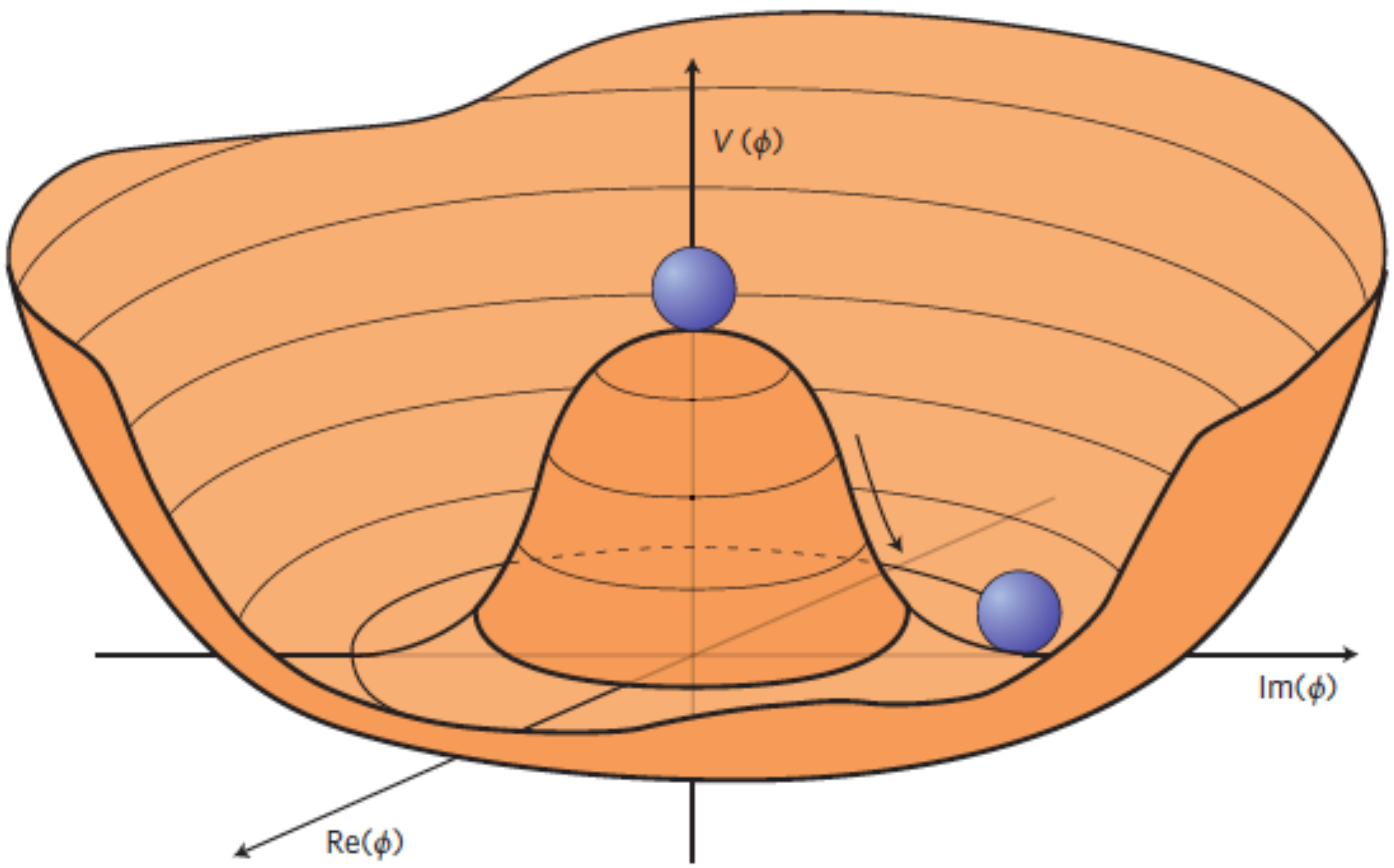
[D. Jeans, G. Wilson ’18]



e^+e^- Higgs factory: high sensitivity to the CP structure of the h125-ττ coupling

Higgs potential: the "holy grail" of particle physics

The simple picture



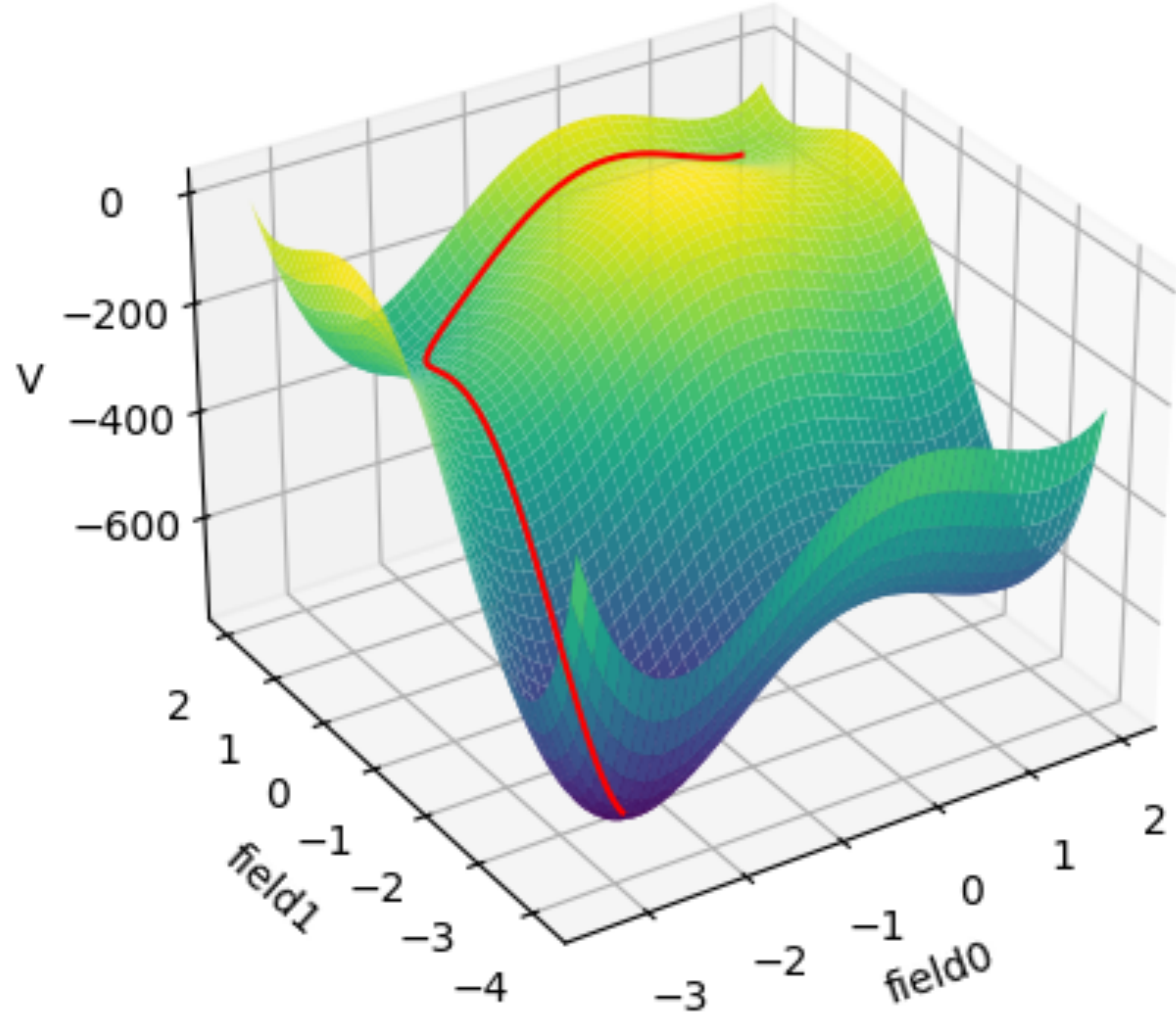
refers to the case of a single Higgs doublet field

If more than one scalar field is present, the Higgs potential is a multi-dimensional function of the components of the different scalar fields

Simple toy example: two singlet-type Higgs fields

[T. Biekötter, F. Campello, G. W. '24]

Tunneling from a local minimum into the global minimum:



⇒ Proceeds via intermediate local minimum

The Higgs potential and vacuum stability

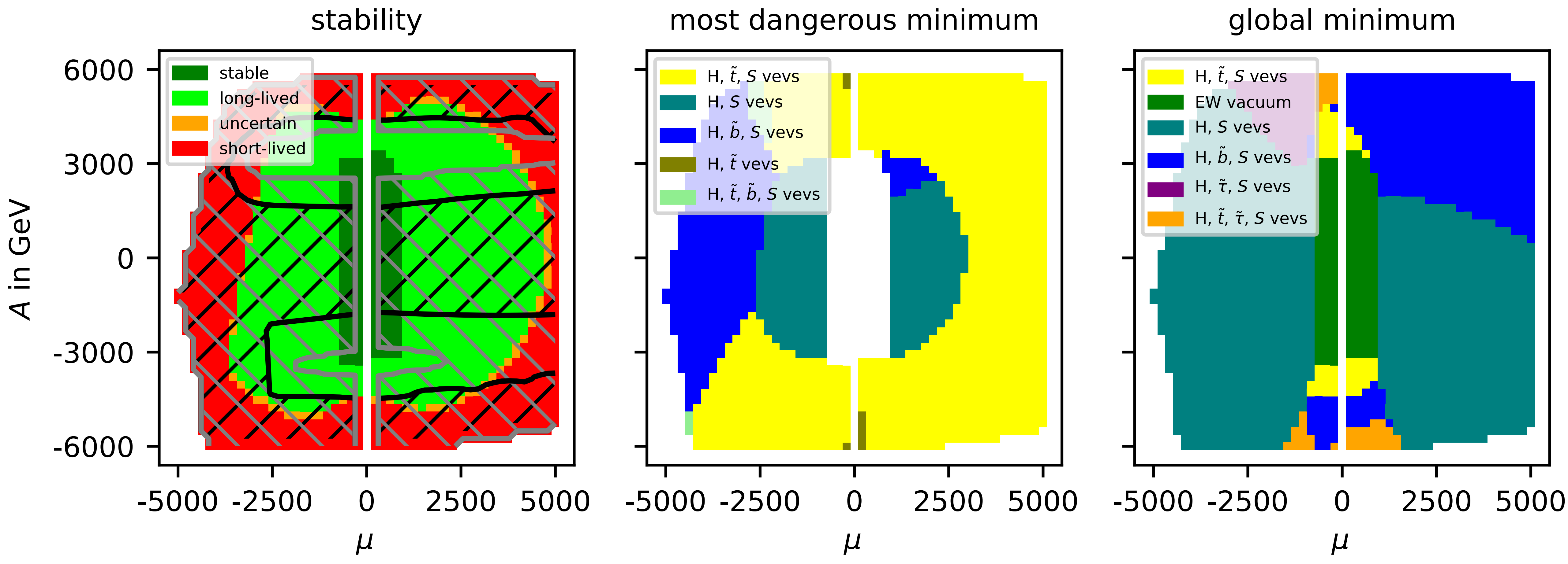
Extended Higgs sectors in general yield additional minima of the Higgs potential; the electroweak minimum may not be the global minimum

Need to check stability of the electroweak vacuum w.r.t. tunneling into deeper minima (analysis at T = 0) *[W.G. Hollik, G. W., J. Wittbrodt '18]*

Improved version of the public code *Evade*

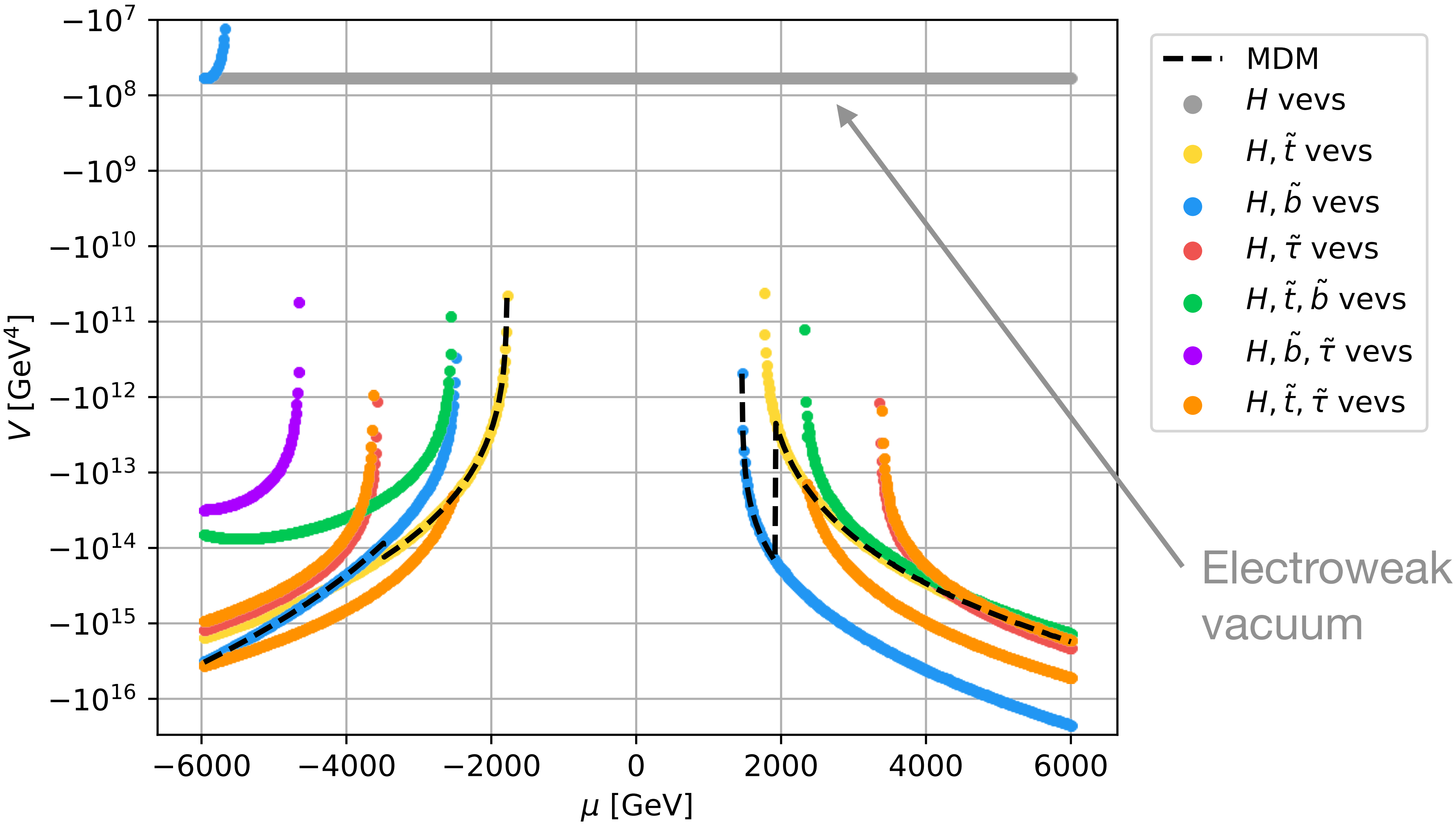
Example: constraints from vacuum stability in the NMSSM on the region allowed by *HiggsBounds* and *HiggsSignals*

[T. Biekötter, F. Campello, G. W. '23]



Depth of stationary points of the Higgs potential

Along line with X_t = 2.8 TeV: *[W.G. Hollik, J. Wittbrodt, G. W. '18]*

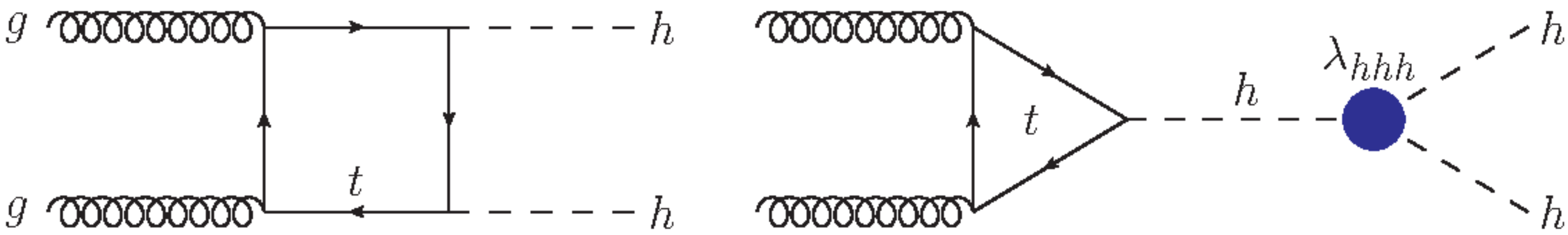


⇒ Most dangerous minimum (MDM) often differs from the global minimum and also from the one that is closest in field space

Trilinear Higgs self-coupling and the Higgs pair production process

Sensitivity to the trilinear Higgs self-coupling from Higgs pair production:

- **Double-Higgs production** → λ_{hhh} enters at LO → **most direct probe of λ_{hhh}**



[Note: Single-Higgs production (EW precision observables) → λ_{hhh} enters at NLO (NNLO)]

e^+e^- Higgs factory:

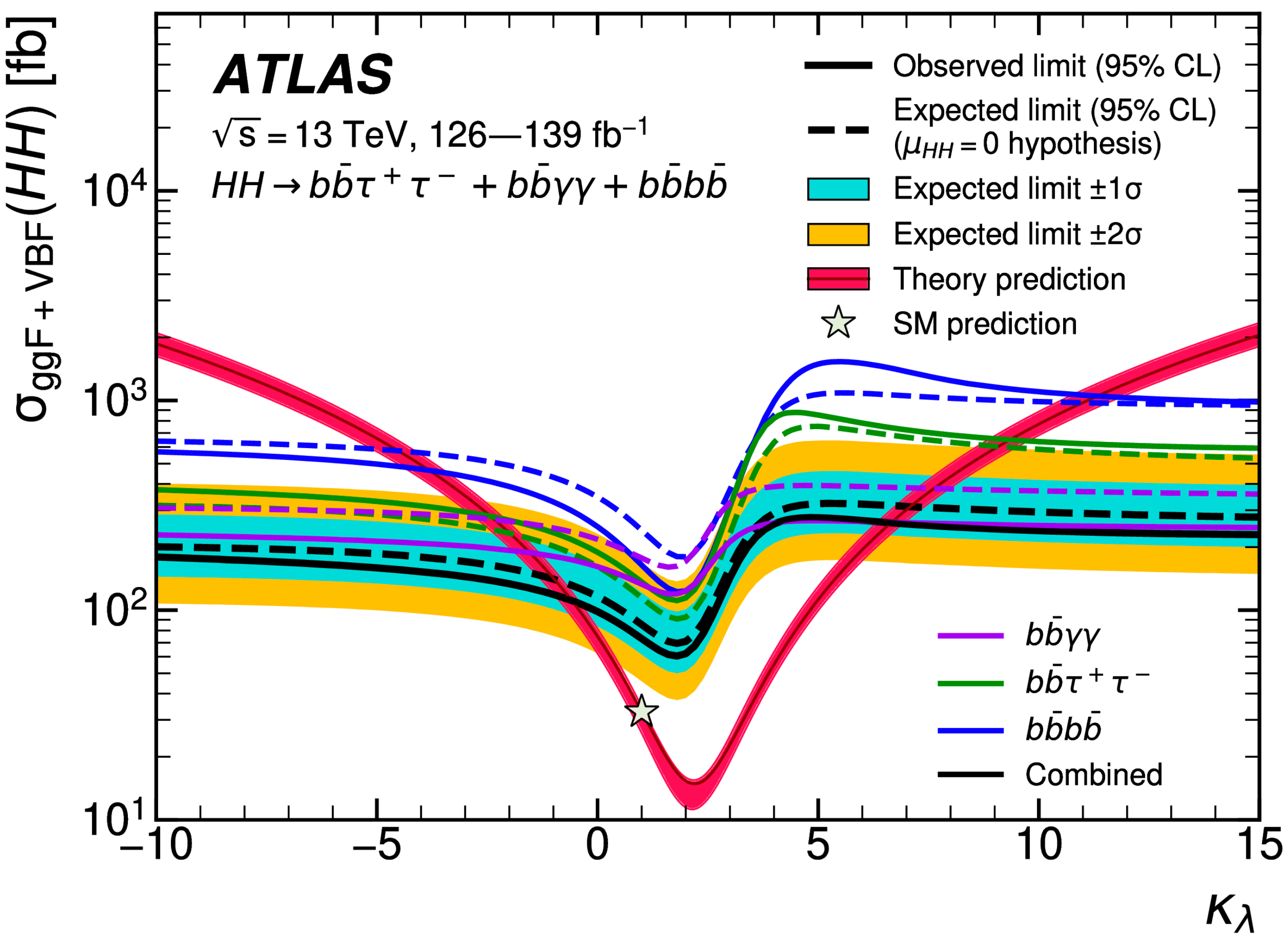
Indirect constraints from measurements of single Higgs production and electroweak precision observables at lower energies are not competitive!

Direct measurement of trilinear Higgs self-coupling at lepton collider with at least 500 GeV c.m. energy will be crucial!

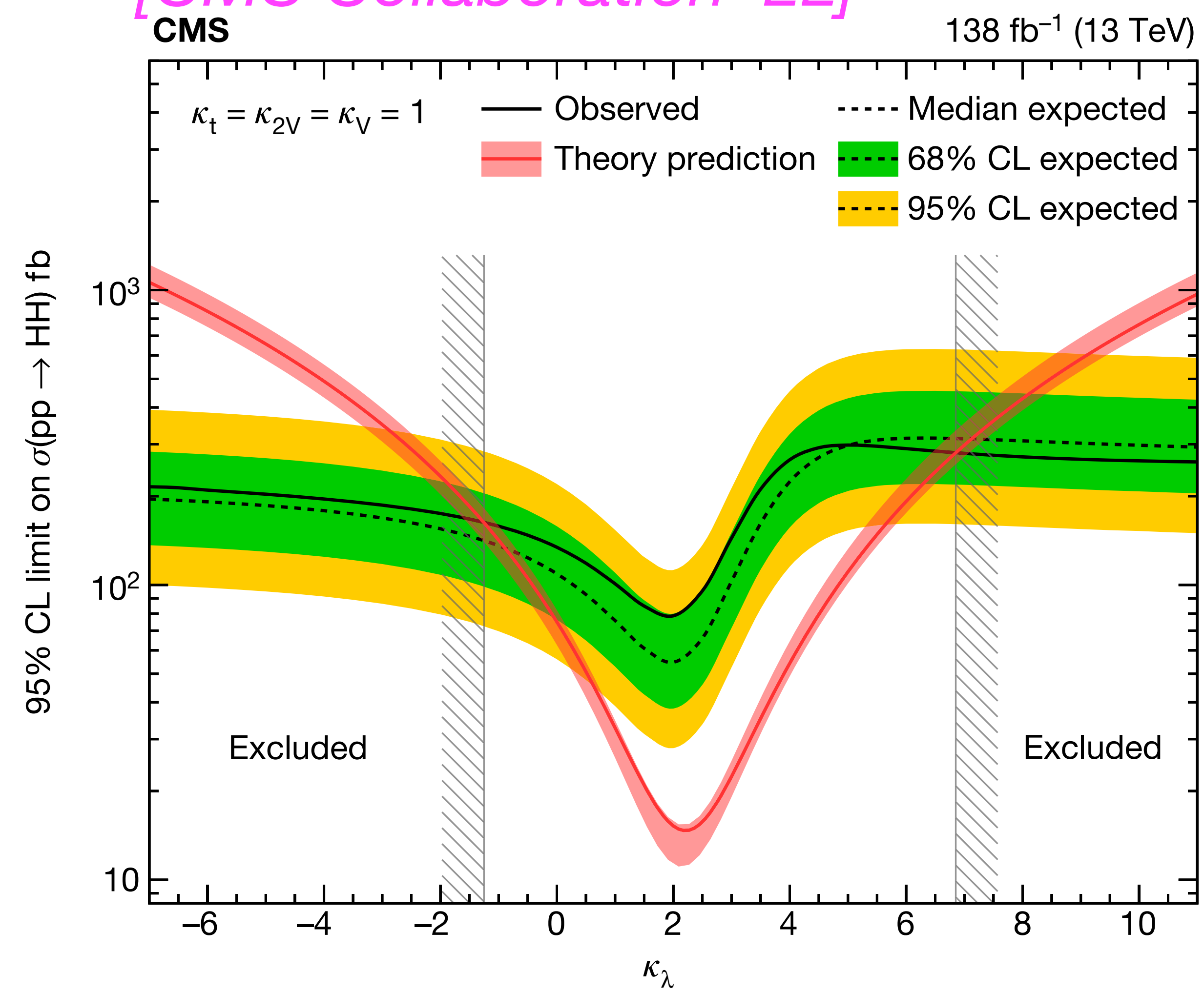
Note: the ``non-resonant” experimental limit on Higgs pair production obtained by ATLAS and CMS depends on $\varkappa_\lambda = \lambda_{hhh} / \lambda_{hhh}^{SM, 0}$

Bound on the trilinear Higgs self-coupling: κ_λ

[ATLAS Collaboration '22]



[CMS Collaboration '22]



Using only information from di-Higgs production and assuming that new physics only affects the trilinear Higgs self-coupling, this limit on the cross section translates to:

ATLAS: $-0.6 < \kappa_\lambda < 6.6$ at 95% C.L. [ATLAS Collaboration '22]

CMS: $-1.2 < \kappa_\lambda < 6.5$ at 95% C.L. [CMS Collaboration '22]

Check of applicability of the experimental limit on $\varkappa_\lambda$

The assumption that new physics only affects the trilinear Higgs self-coupling is expected to hold at most approximately in realistic models

BSM models can modify Higgs pair production via resonant and non-resonant contributions

The current experimental limit can only probe scenarios with large deviations from the SM

⇒ Direct application of the experimental limit on $\varkappa_\lambda$ is possible if sub-leading effects are less relevant

Two-loop predictions for the trilinear Higgs coupling in the 2HDM vs. current experimental bounds

[H. Bahl, J. Braathen, G. W. ’22]

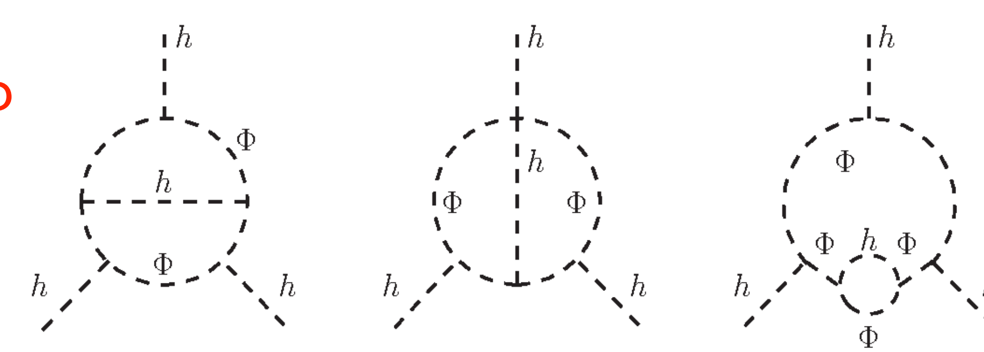
The largest loop corrections to λ_{hhh} in the 2HDM are induced by the quartic couplings between two SM-like Higgs bosons h (where one external Higgs is possibly replaced by its vacuum expectation value) and two BSM Higgs bosons ϕ of the form

$$g_{hh\Phi\Phi} = -\frac{2(M^2 - m_\Phi^2)}{v^2} \qquad \Phi \in \{H, A, H^\pm\}$$

Leading two-loop corrections involving heavy BSM Higgses and the top quark in the effective potential approximation

[J. Braathen, S. Kanemura ’19, ’20]

⇒Incorporation of the highest powers in $g_{hh\phi\phi}$



Analysis is carried out in the alignment limit of the 2HDM ($\alpha = \beta - \pi/2$)

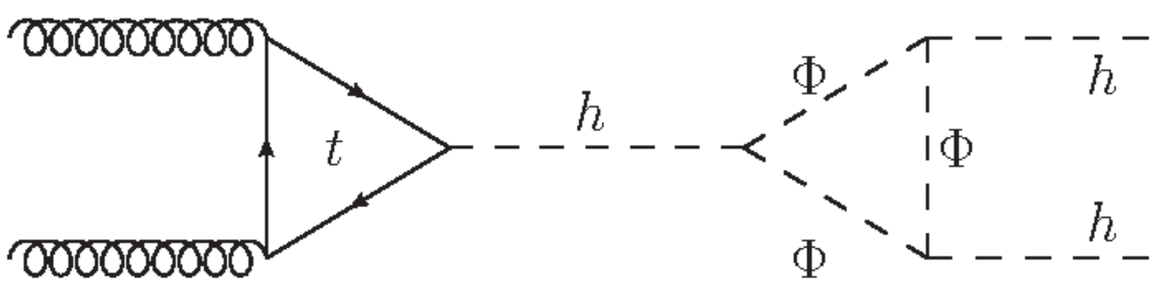
⇒h has SM-like tree-level couplings

Check of applicability of the experimental limit on ϰ$_\lambda$

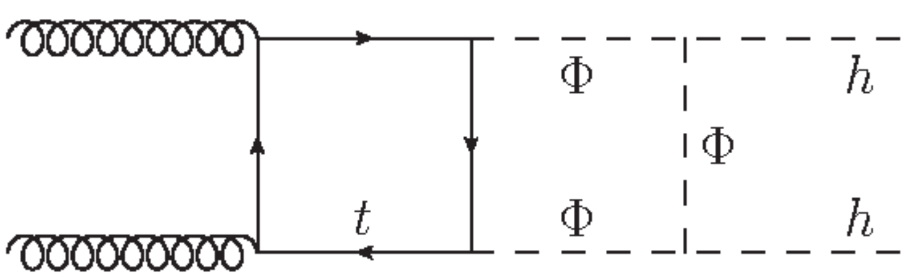
Alignment limit: h has SM-like tree-level couplings

Resonant contribution to Higgs pair production with H or A in the s channel is absent in the alignment limit

The dominant new-physics contributions enter via trilinear coupling



$\propto \mathcal{O}(y_t g^3_{hh\Phi\Phi})$ ***included***



$\propto \mathcal{O}(y_t^2 g^2_{hh\Phi\Phi})$ *not included*

⇒The leading effects in $g_{hh\phi\phi}$ to the Higgs pair production process are correctly incorporated at the 1- and 2-loop order via the corrections to the trilinear Higgs coupling!

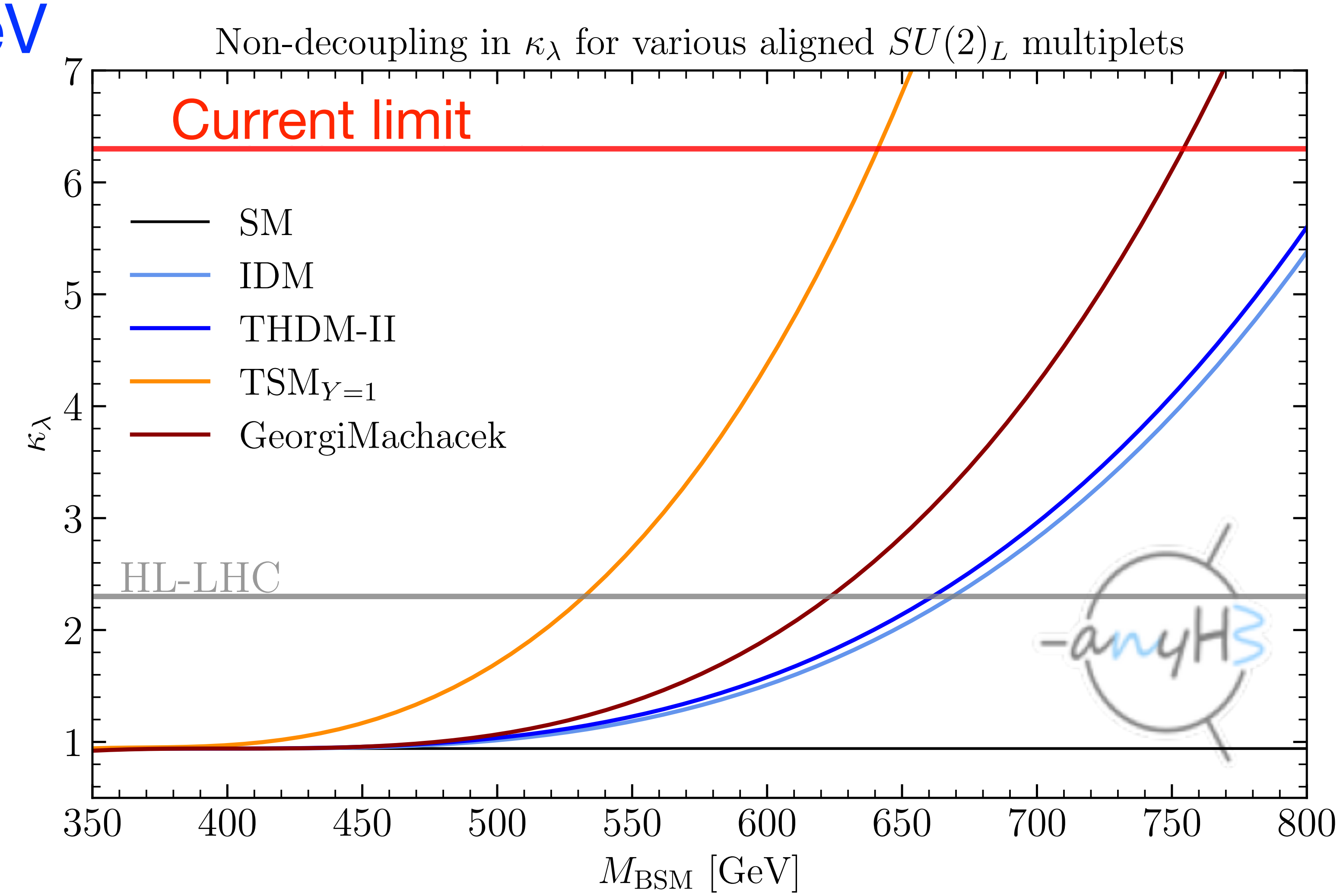
Higgs self-couplings in extended Higgs sectors

Effect of splitting between BSM Higgs bosons:

Very large corrections to the Higgs self-couplings, while all couplings of h_{125} to gauge bosons and fermions are SM-like (tree-level couplings agree with the SM in the alignment limit)

[H. Bahl, J. Braathen, M. Gabelmann, G. W. '23]

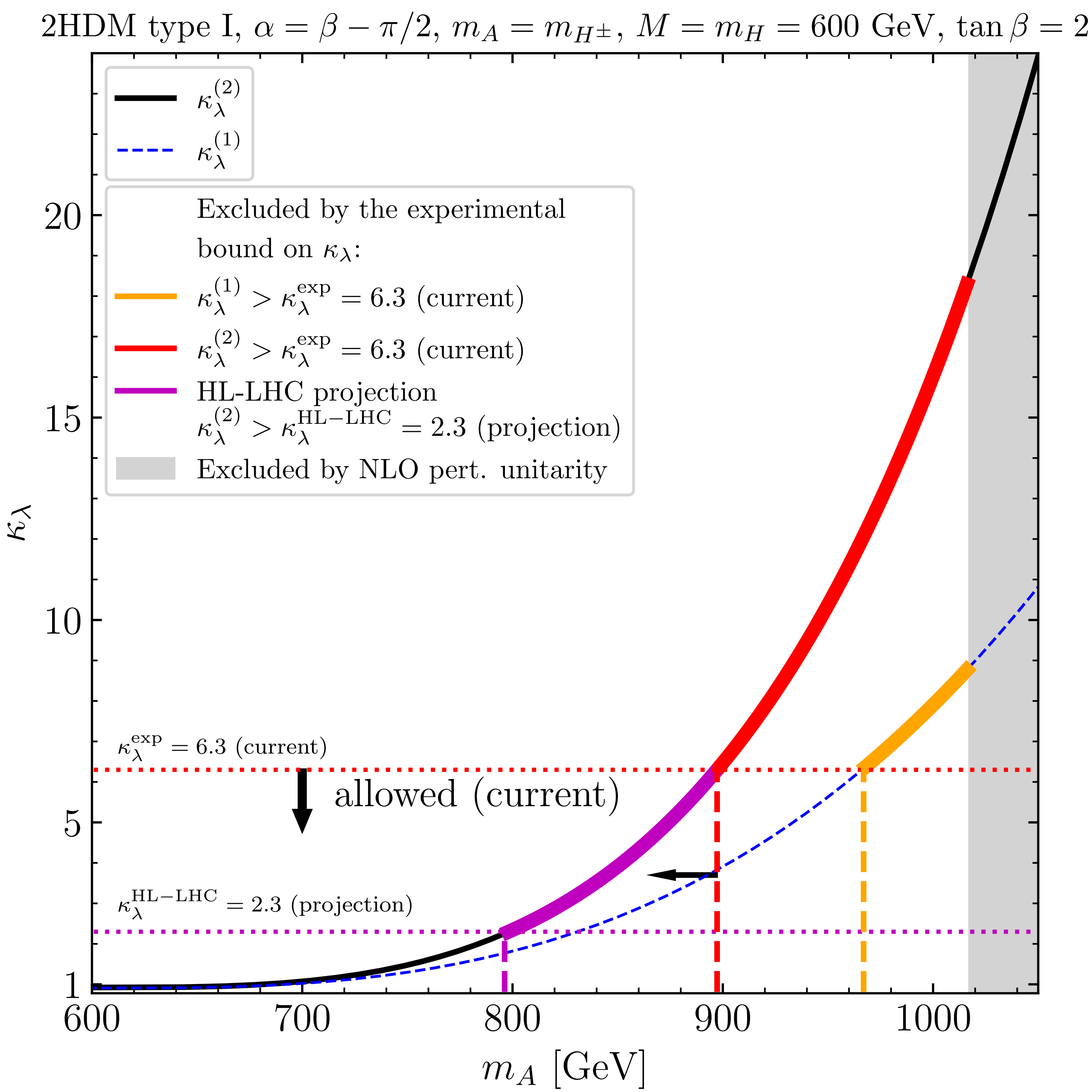
M_L = 400 GeV



Trilinear Higgs coupling: current experimental limit vs. prediction from extended Higgs sector (2HDM)

Prediction for ϰλ up to the two-loop level:

[H. Bahl, J. Braathen, G. W. '22, Phys. Rev. Lett. 129 (2022) 23, 231802]

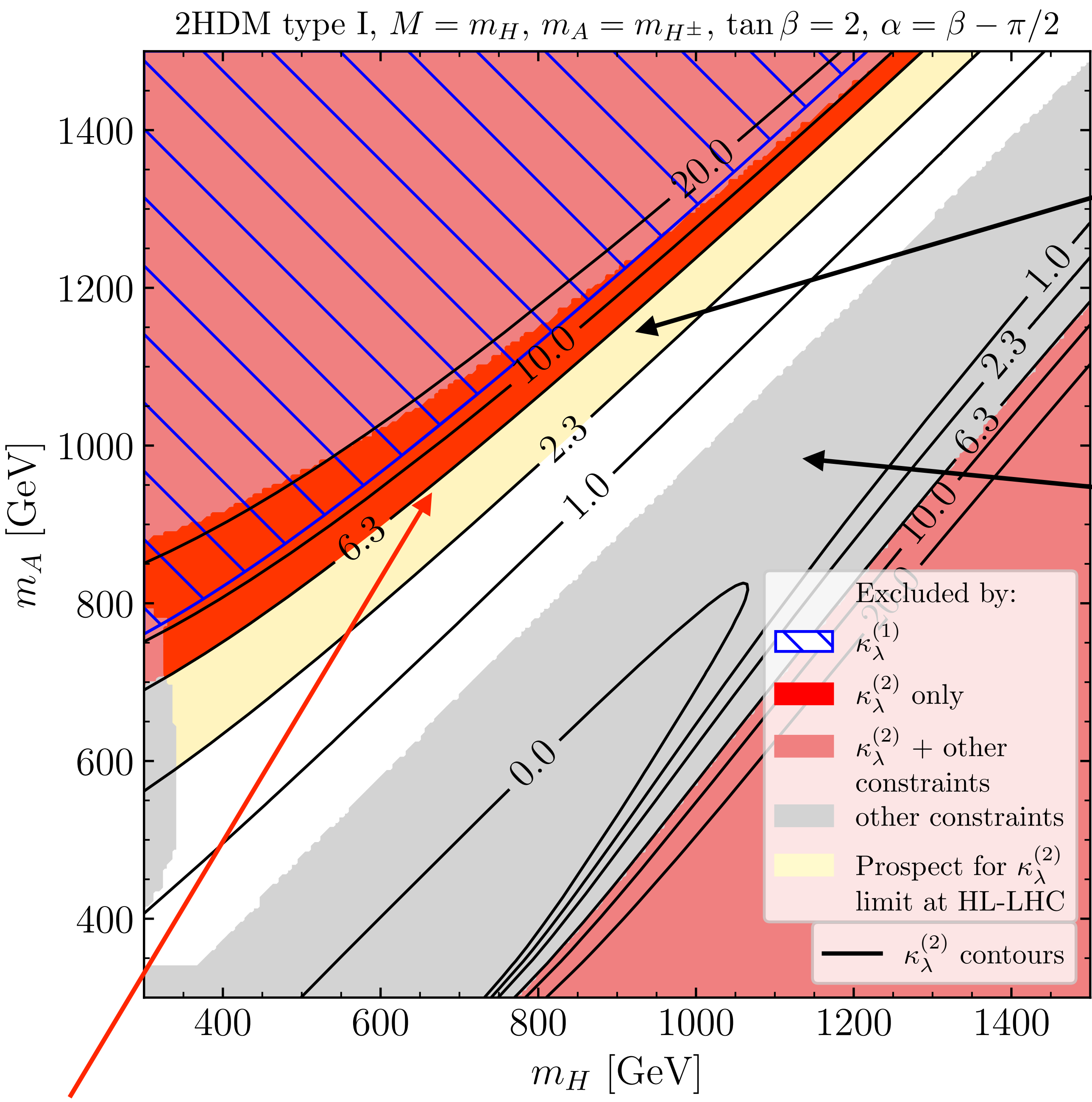


⇒ Current experimental limit excludes important parameter region that would be allowed by all other constraints!

Experimental limit on the trilinear Higgs coupling already has sensitivity to probe extended Higgs sectors!

Constraints in the mass plane of H and A

[H. Bahl, J. Braathen, G. W. '22]



Sensitivity to $\varkappa_\lambda$ at the HL-LHC

Excluded by other constraints: Higgs physics, boundedness from below, NLO perturbative unitarity, …

⇒ LHC limits exclude parameter regions that would be allowed by all other constraints; high sensitivity of future limits / measurements!

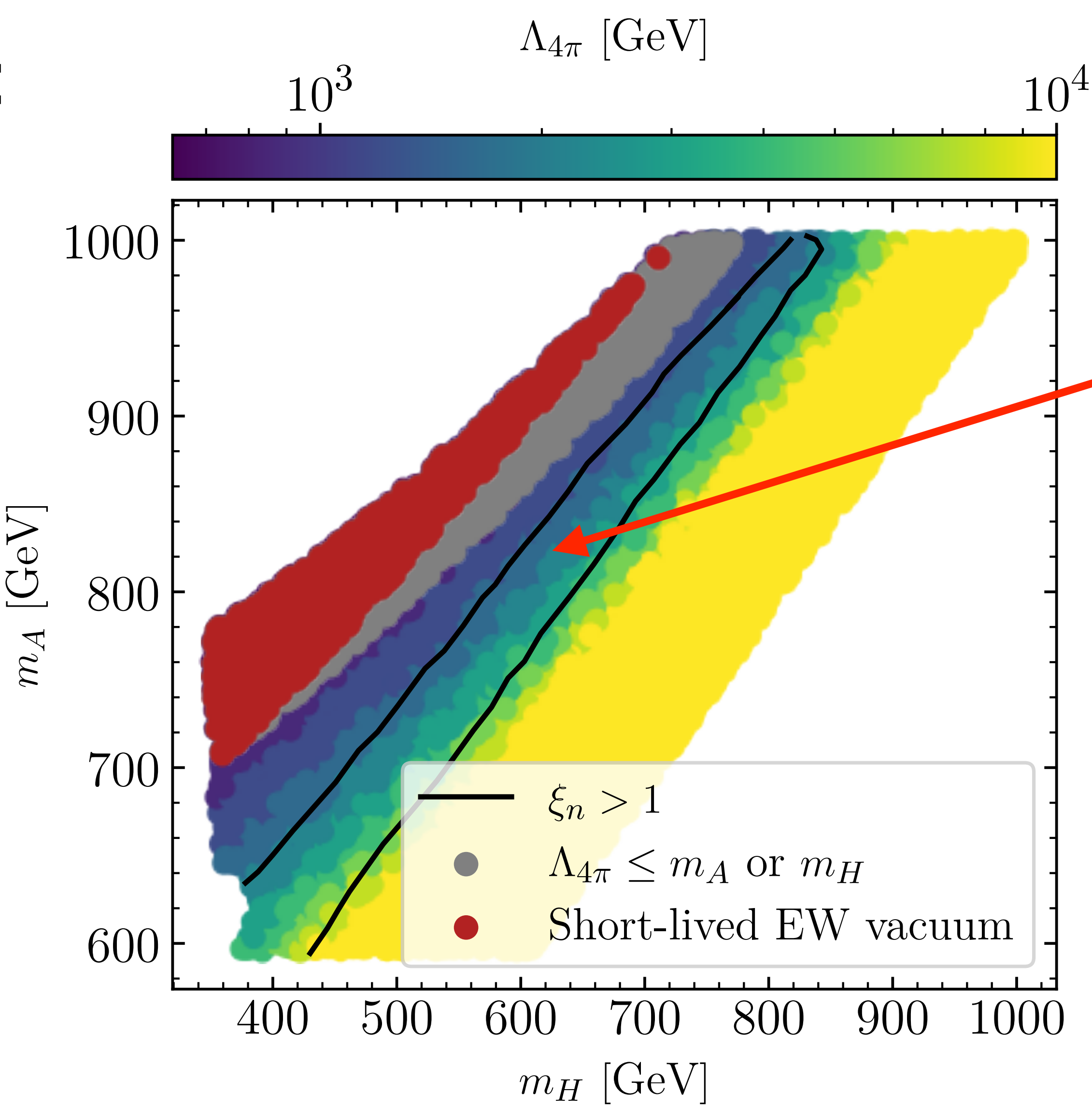
Connection between the trilinear Higgs coupling and the evolution of the early Universe

2HDM, N2HDM, … : the parameter region giving rise to a strong first-order EWPT, which may cause a detectable gravitational wave signal, is correlated with an enhancement of the trilinear Higgs self-coupling and with ``smoking gun” signatures at the LHC

[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. ’22]

2HDM of type II:

alignment limit,
tanβ = 3

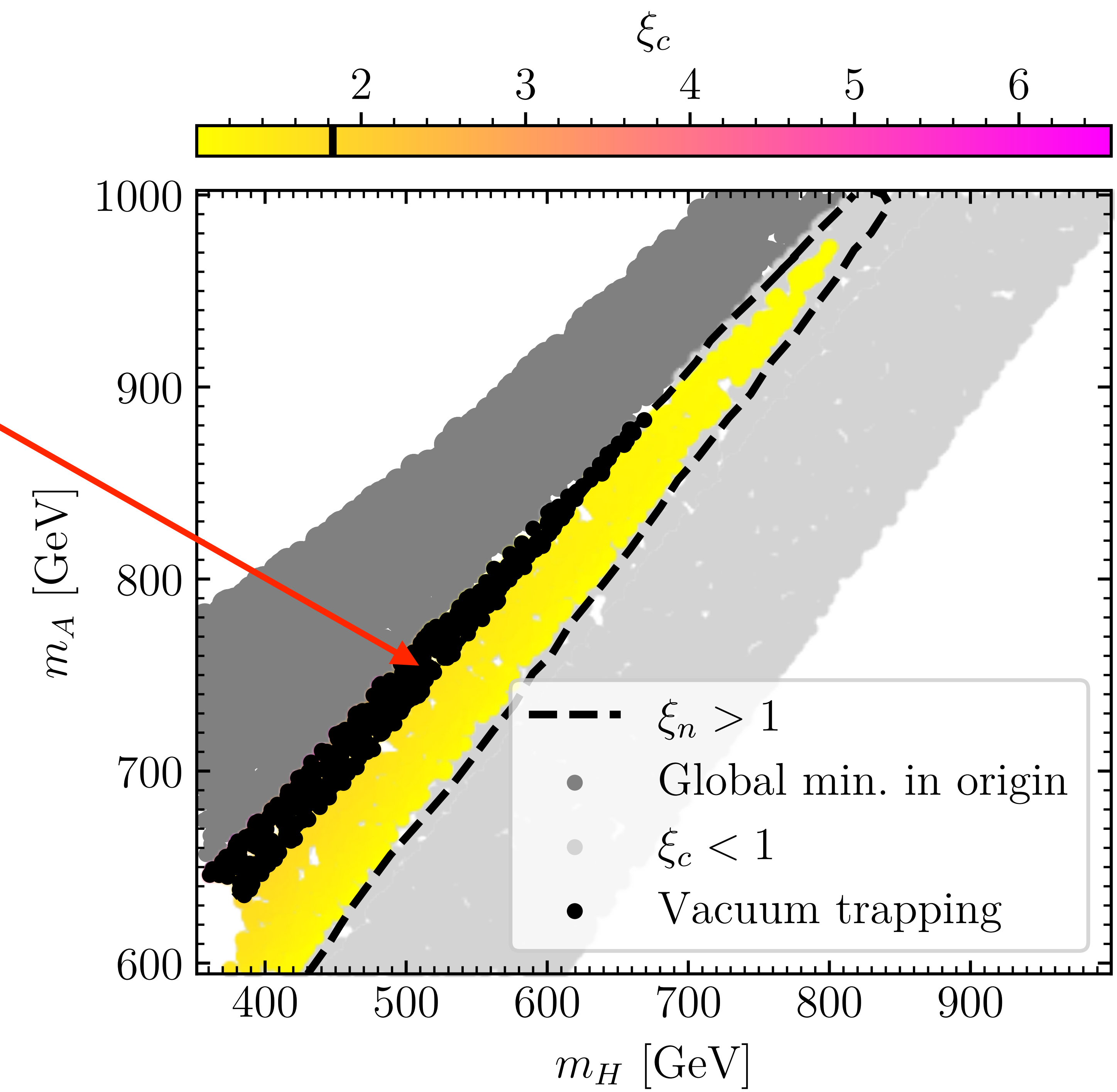


Parameter region giving rise to a strong first-order EWPT

2HDM of type II: region of strong first-order EWPT

[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. ’22]

Constraints from ``vacuum trapping”: the universe may remain ``trapped” in a symmetry-conserving vacuum at the origin, because the conditions for a transition into the deeper EW-breaking minimum are not fulfilled



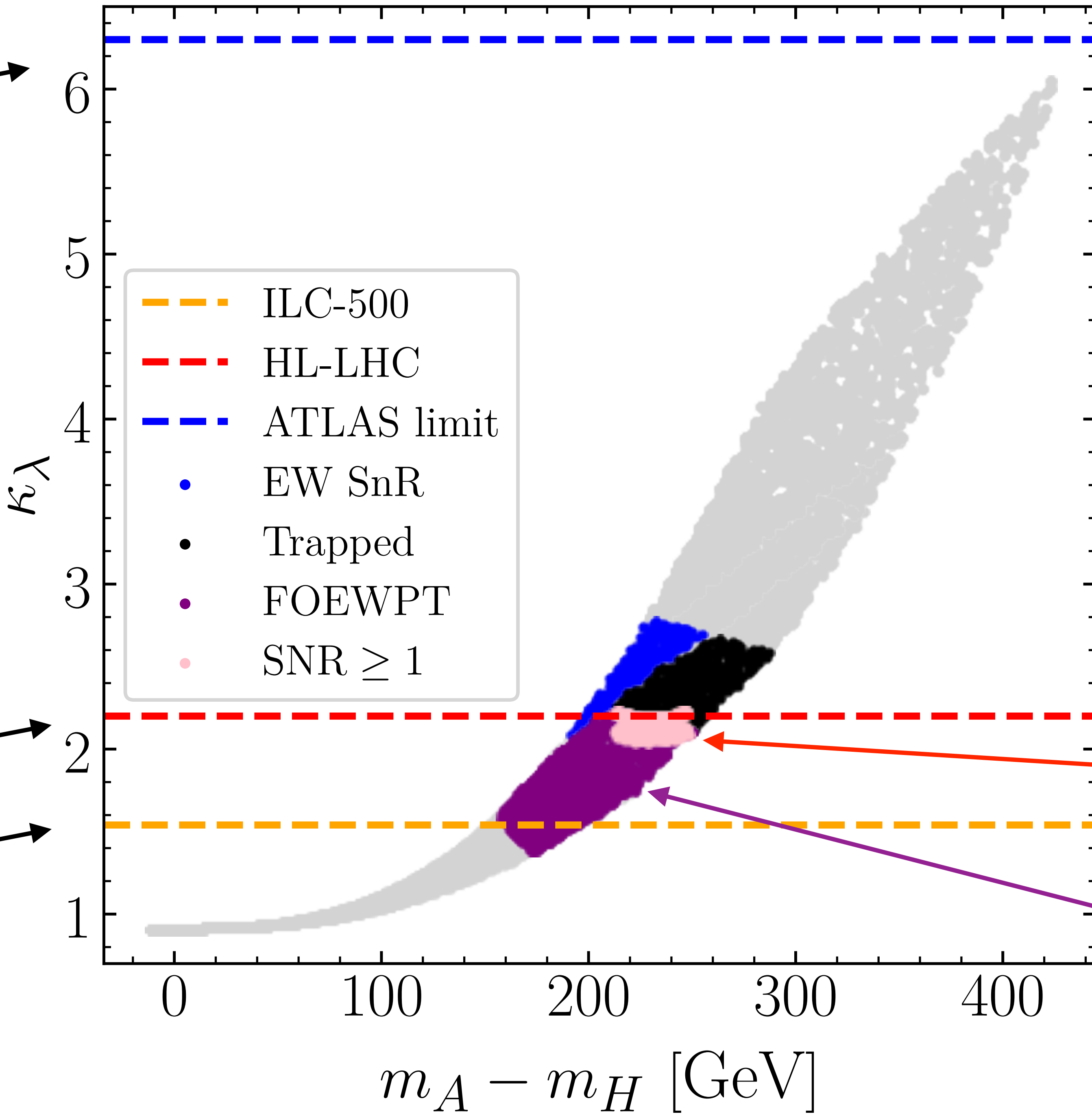
Relation between trilinear Higgs coupling and strong first-order EWPT with potentially observable GW signal

[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. ’22]

current bound

HL-LHC sensitivity

ILC sensitivity



alignment limit, tanβ = 3

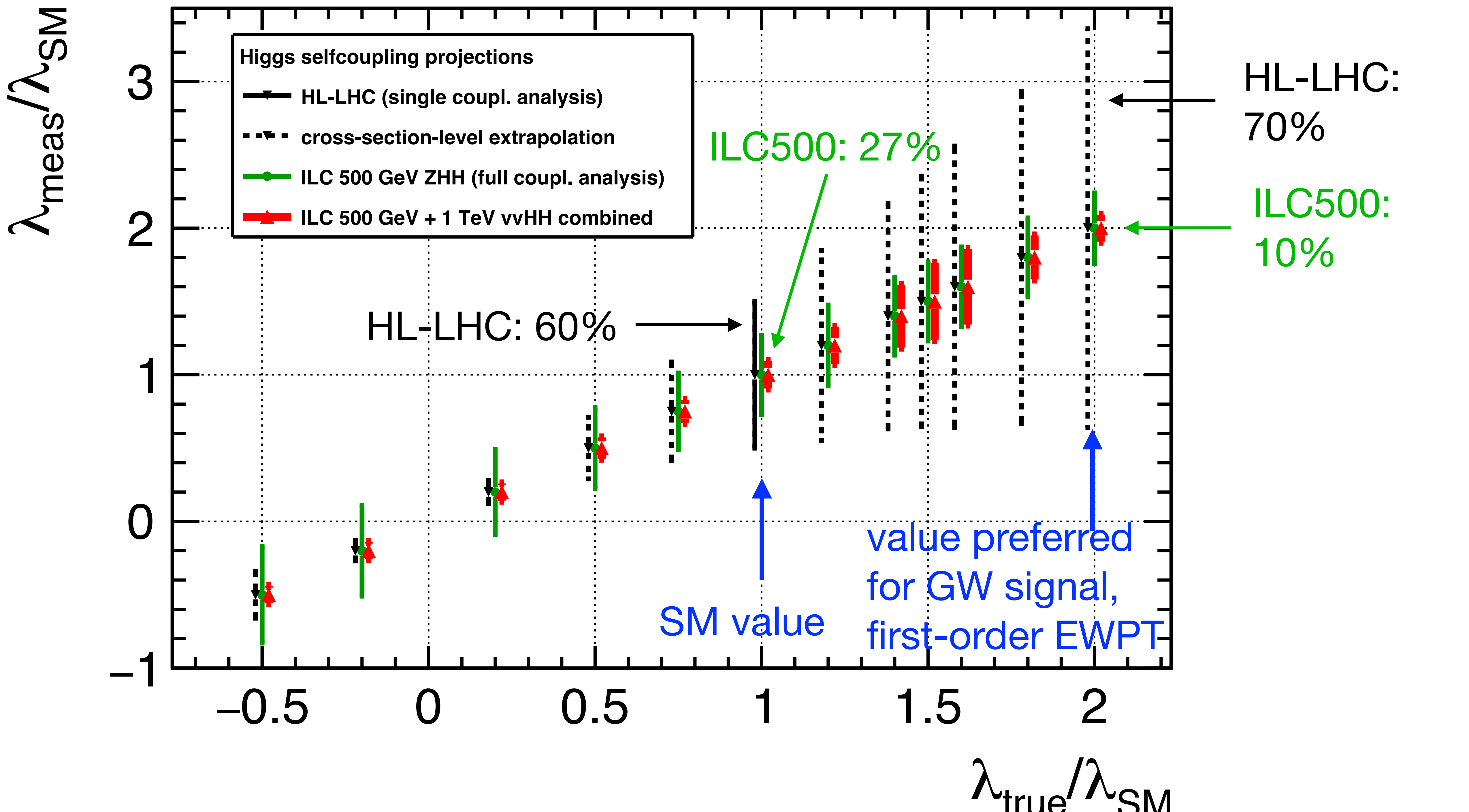
region with potentially observable gravitational wave (GW) signal

region with strong first-order EWPT

⇒ Region with potentially detectable GW signal and strong first-order EWPT is correlated with significant deviation of κ_λ from SM value

Prospects for measuring the trilinear Higgs coupling: HL-LHC vs. ILC (500 GeV, Higgs pair production)

[J. List et al. '21]

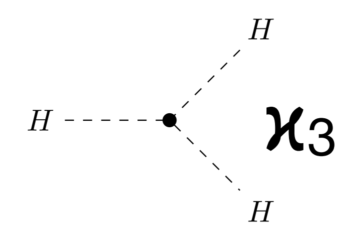


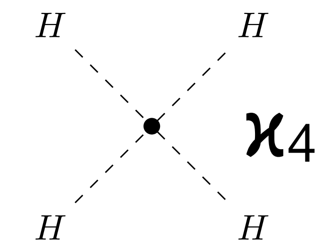
⇒ For $\varkappa_\lambda \approx 2$: much better prospects for ILC500 than for HL-LHC

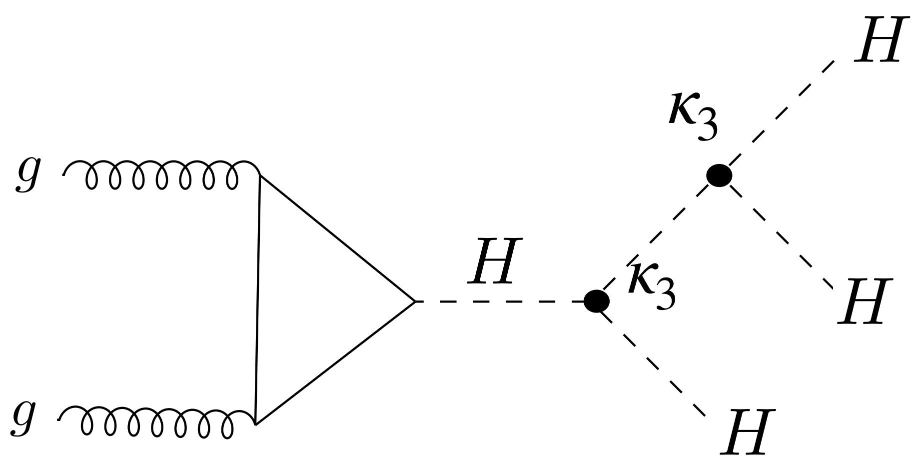
Reason: different interference contributions

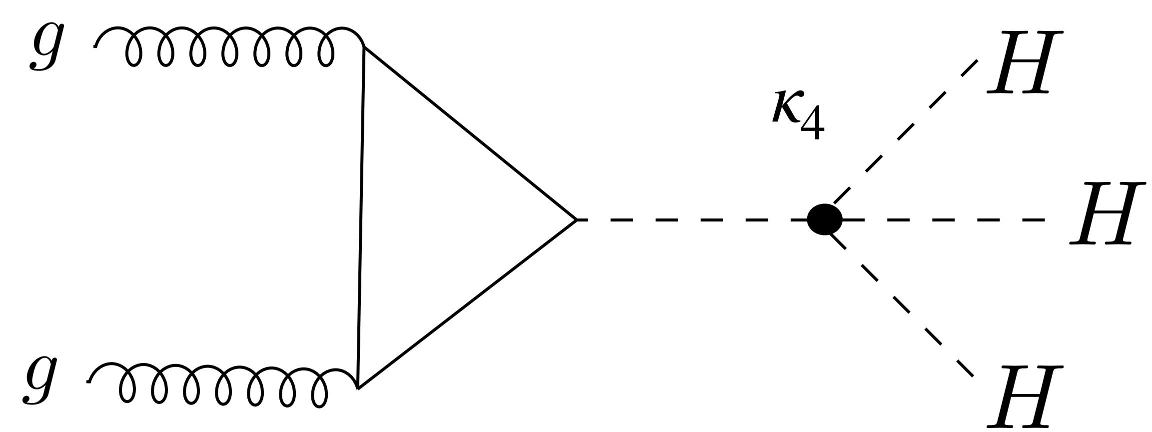
Exploring HHH production w.r.t. Higgs self-couplings

Triple Higgs production depends on $\varkappa_3$ and $\varkappa_4$!









Is it possible to obtain bounds from triple Higgs production on $\varkappa_3$ and $\varkappa_4$ that go beyond the existing theoretical bounds from perturbative unitarity? Potential for $\varkappa_3$ constraints beyond the ones from di-Higgs production?

How big could the deviations in $\varkappa_4$ from the SM value (= 1) be in BSM scenarios?

Bounds from perturbative unitarity

- Process relevant for κ_3, κ_4 is $HH \to HH$ scattering (see also [Liu et al ` 18])

- Jacob-Wick expansion allows to extract partial waves

$$\beta(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2xz$$

Wigner functions

$$a^J_{fi} = \frac{\beta^{1/4}(s, m^2_{f_1}, m^2_{f_1})\beta^{1/4}(s, m^2_{i_1}, m^2_{i_1})}{32\pi s} \int_{-1}^{1} \mathrm{d}\cos\theta \, \mathcal{D}^J_{\mu_i \mu_f} \, \mathcal{M}(s, \cos\theta)$$

- Tree level unitarity:

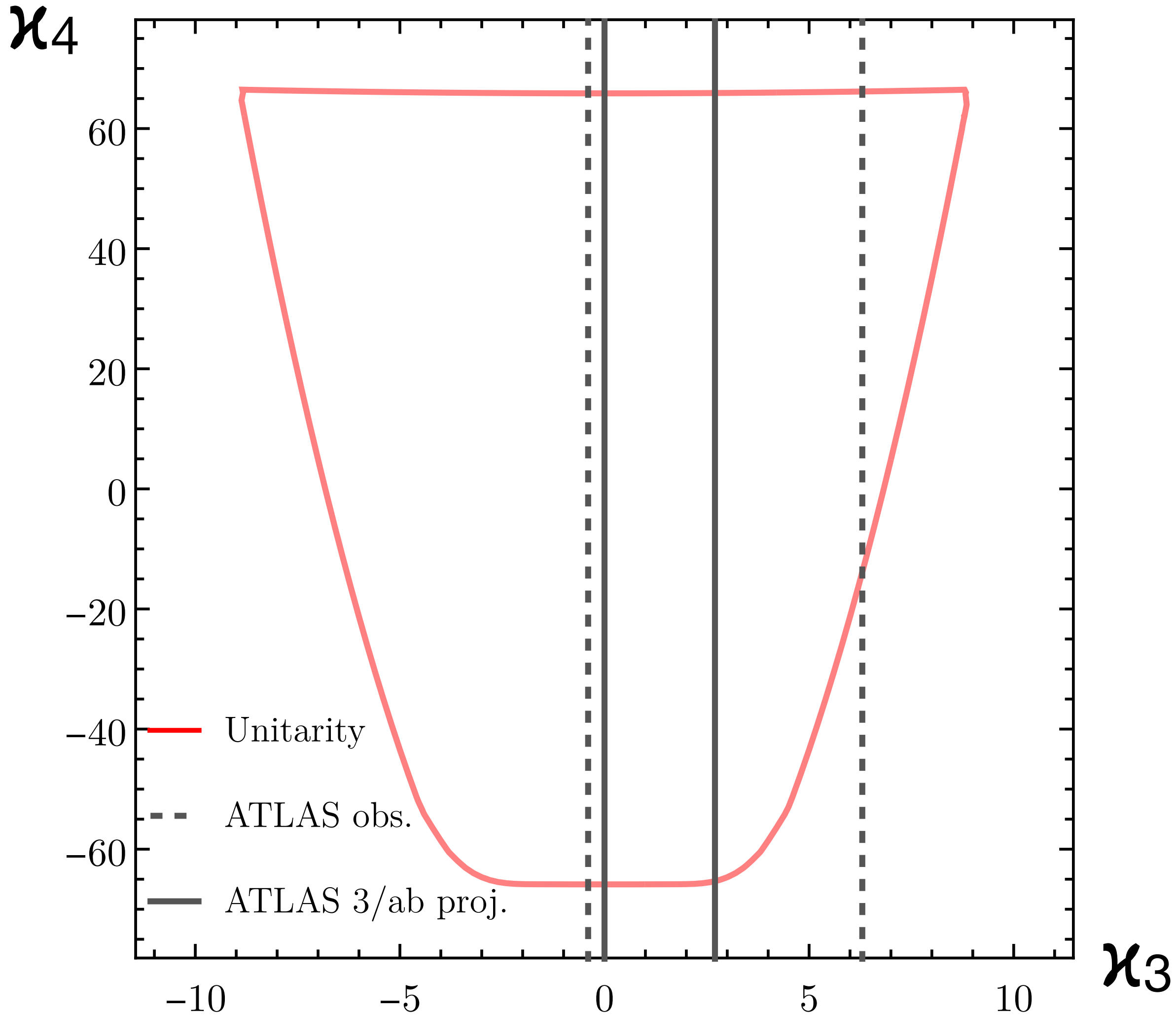
$$\mathrm{Im} a^0_{ii} \geq |a^0_{ii}|^2 \implies |\mathrm{Re} a^0_{ii}| \leq \frac{1}{2}$$

95 % CL

ATLAS current bounds: $[-0.4, 6.3]$

CMS & ATLAS HH projections: $[0.1, 2.3]$

[ATLAS 2211.01216]
[CERN Yellow Rep. 1902.00134]



Possible size of BSM contributions: SMEFT: effects of higher-dimensional operators

Linear power expansion for higher order terms in Λ^{-1} orders:

[Boudjema, Chopin `96]
[Maltoni, Pagani, Zhao `18]

$$V_{\rm BSM} = \frac{C_6}{\Lambda^2}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^3 + \frac{C_8}{\Lambda^4}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^4 + \ldots$$

Contributions to κ_3, κ_4:

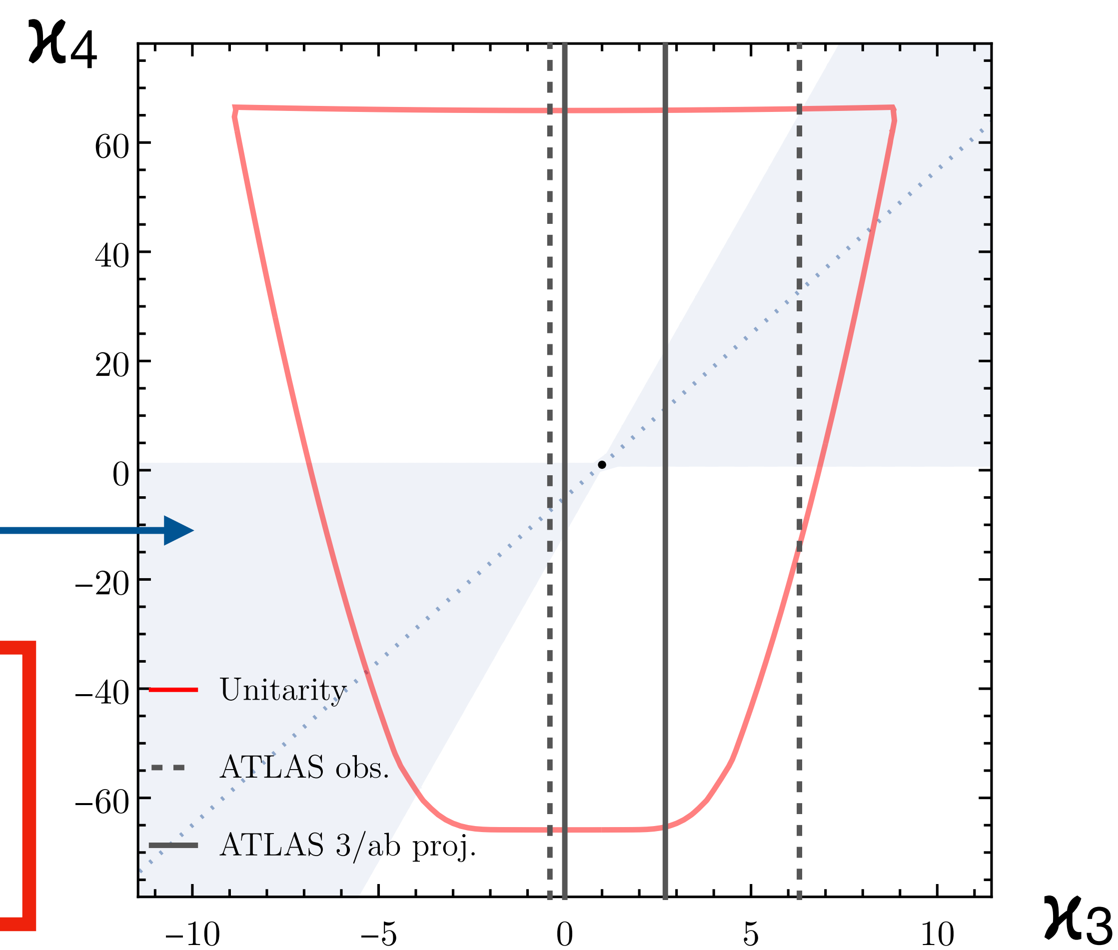
$$(\kappa_3 - 1) = \frac{C_6 v^2}{\lambda\Lambda^2}\,,$$

$$(\kappa_4 - 1) = \frac{6C_6 v^2}{\lambda\Lambda^2} + \frac{4C_8 v^4}{\lambda\Lambda^4}$$

vanishing dimension-8 →

$$\simeq 6(\kappa_3 - 1) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Shaded region: $\frac{4C_8 v^4}{\lambda\Lambda^4} < \frac{6C_6 v^2}{\lambda\Lambda^2}$ →



Electroweak Chiral Lagrangian (HEFT):
Higgs introduced as singlet and κ_3 and κ_4 are **free parameters** →probes **non-linearity**

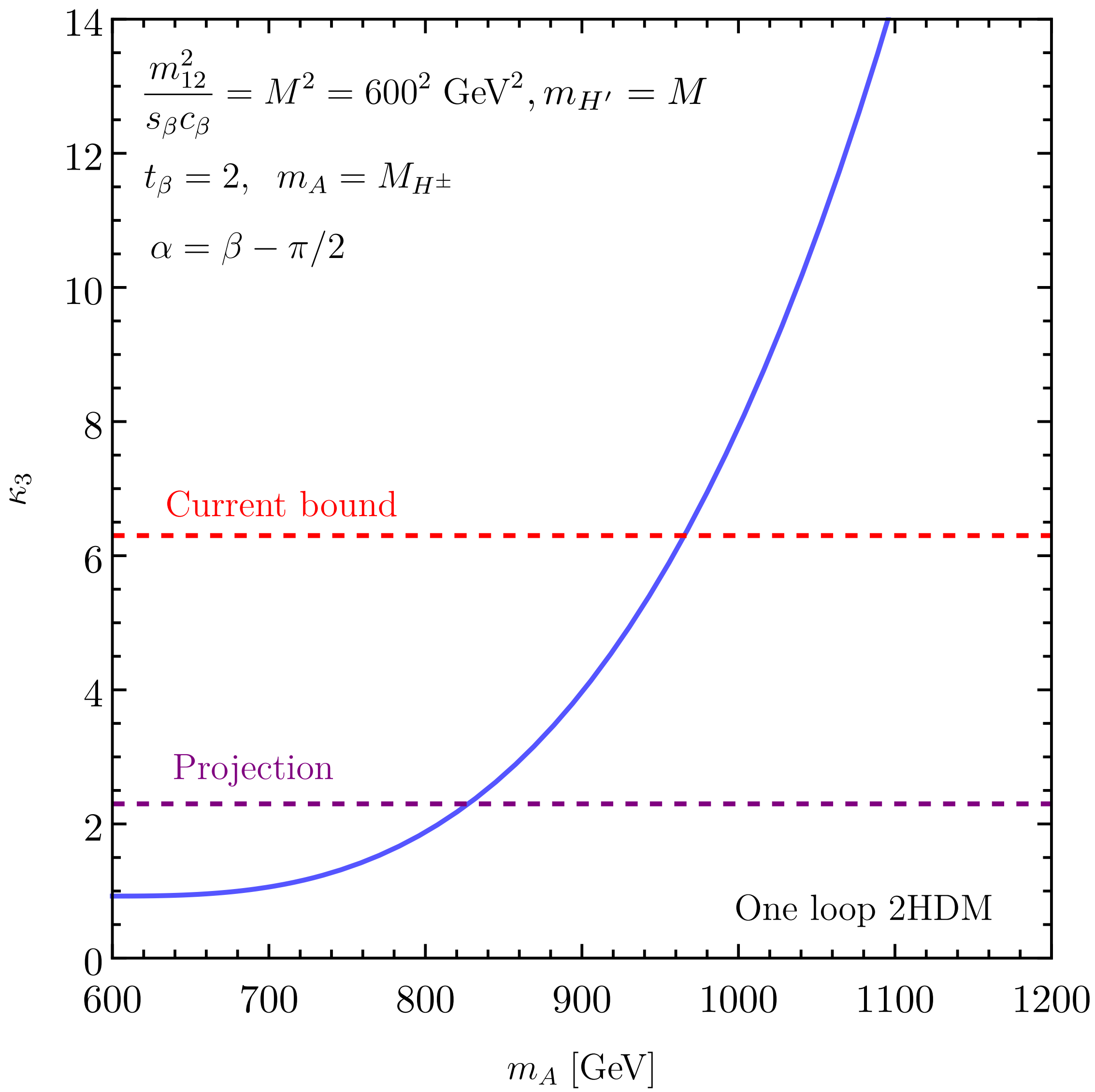
⇒Deviation in ϰ4 enhanced by factor 6!

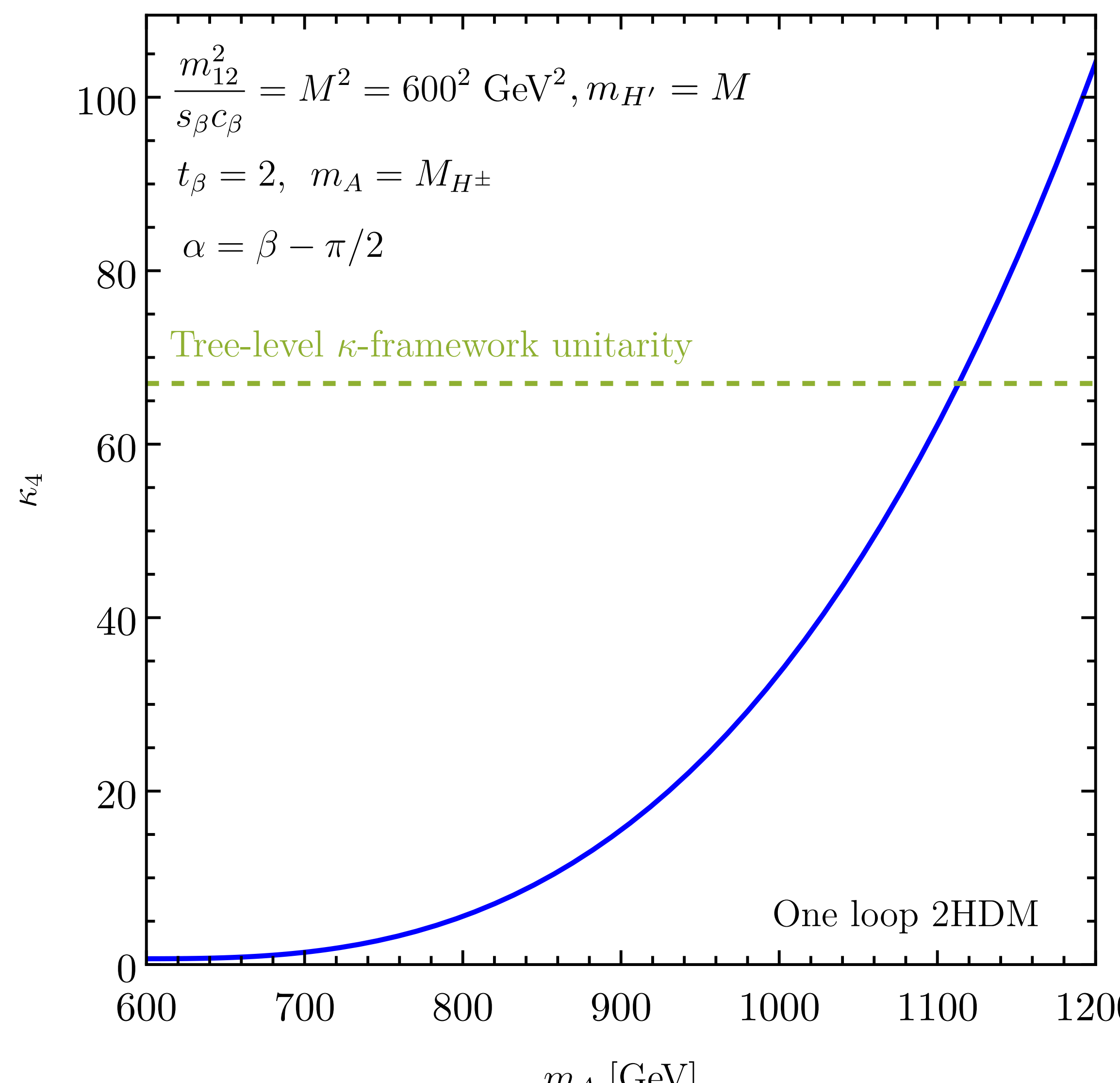
Model example: 2HDM, $\varkappa_3$ (see above) vs. $\varkappa_4$

- Benchmark Point of [Bahl, Braathen, Weiglein `22] → cross-check κ_3 result (also with anyH3)
- Expectedly deviations in κ_3 induce sizeable deviations in κ_4

$$\kappa_i = \frac{\Gamma_i^{(0)} + \hat{\Gamma}_i^{(1)}}{\Gamma_{\mathrm{SM},i}^{(0)}}$$

$$i \in \{3H, 4H\}$$

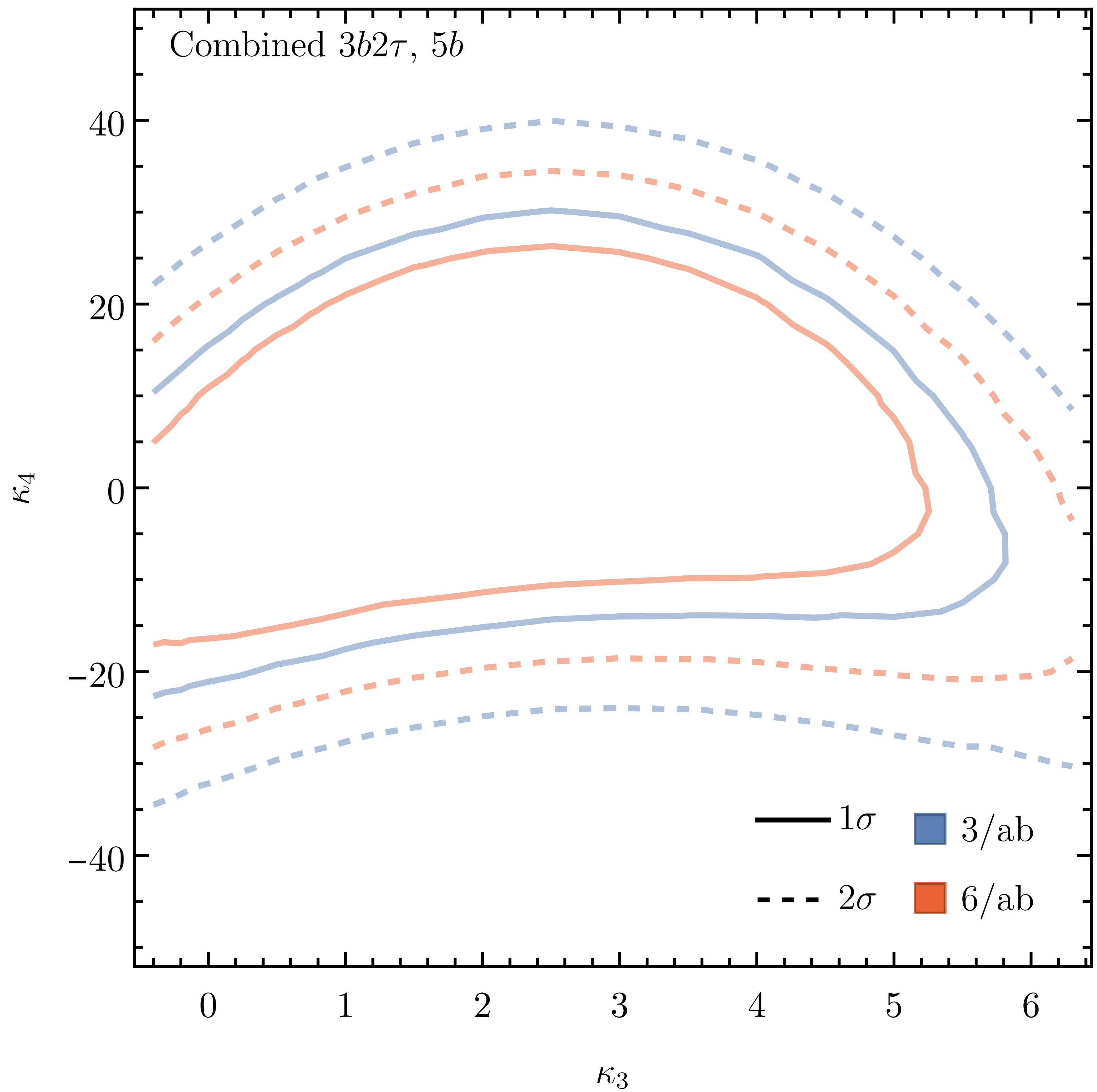




Prospects for the HL-LHC: 6b and 4b2τ channels comb.

- **Assumption:** No correlations

[P. Stylianou, G. W. '24]



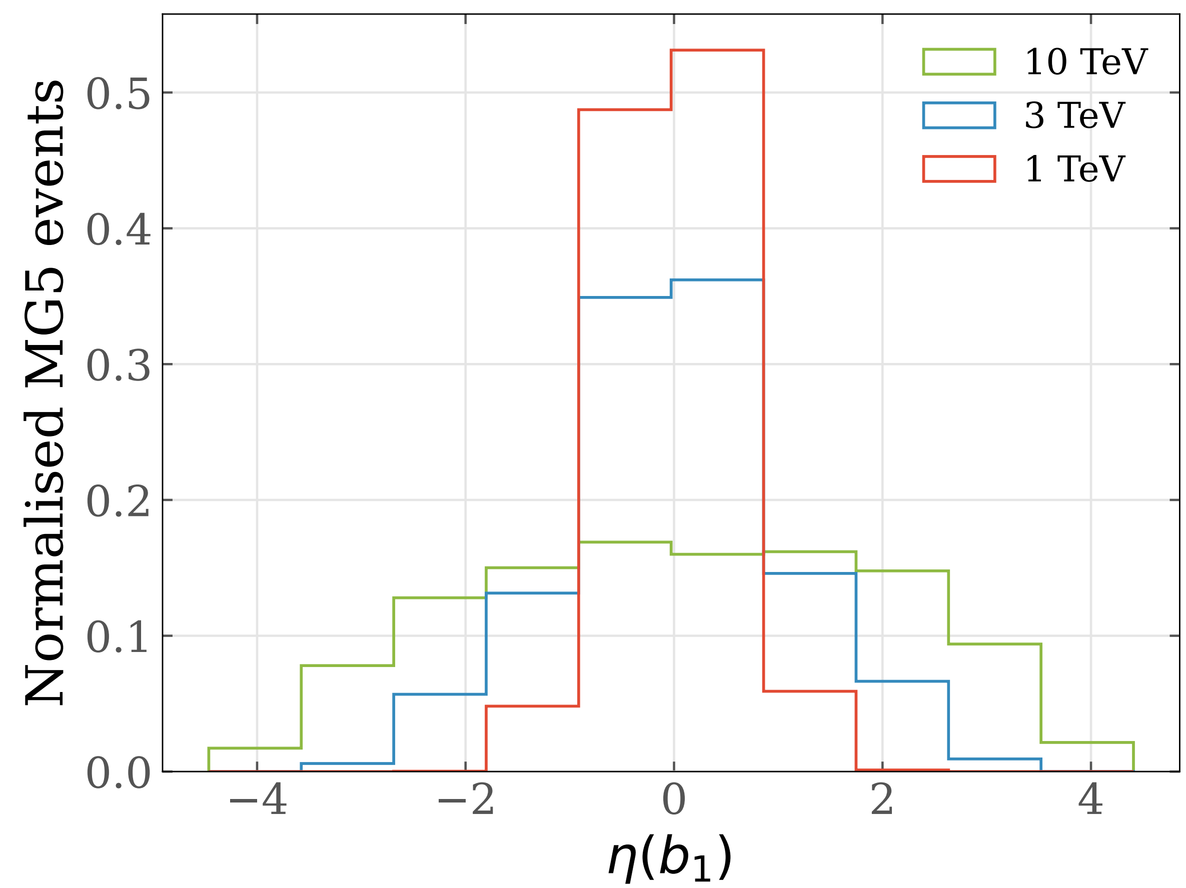
Combination of further channels and improvements of **tagging/reconstruction** methods could enhance results further

Prospects for future lepton colliders

- Inclusive $\ell\ell \to HHH + X$ analysis with $H \to b\bar{b}$
  - At least 5 tagged b-quarks with $p_T(b) > 30$ GeV
  - Tagging efficiency: $80\,\%$

- **Important:** For high energies b-quarks are not only in the central part of detector → requires extended tagging capabilities

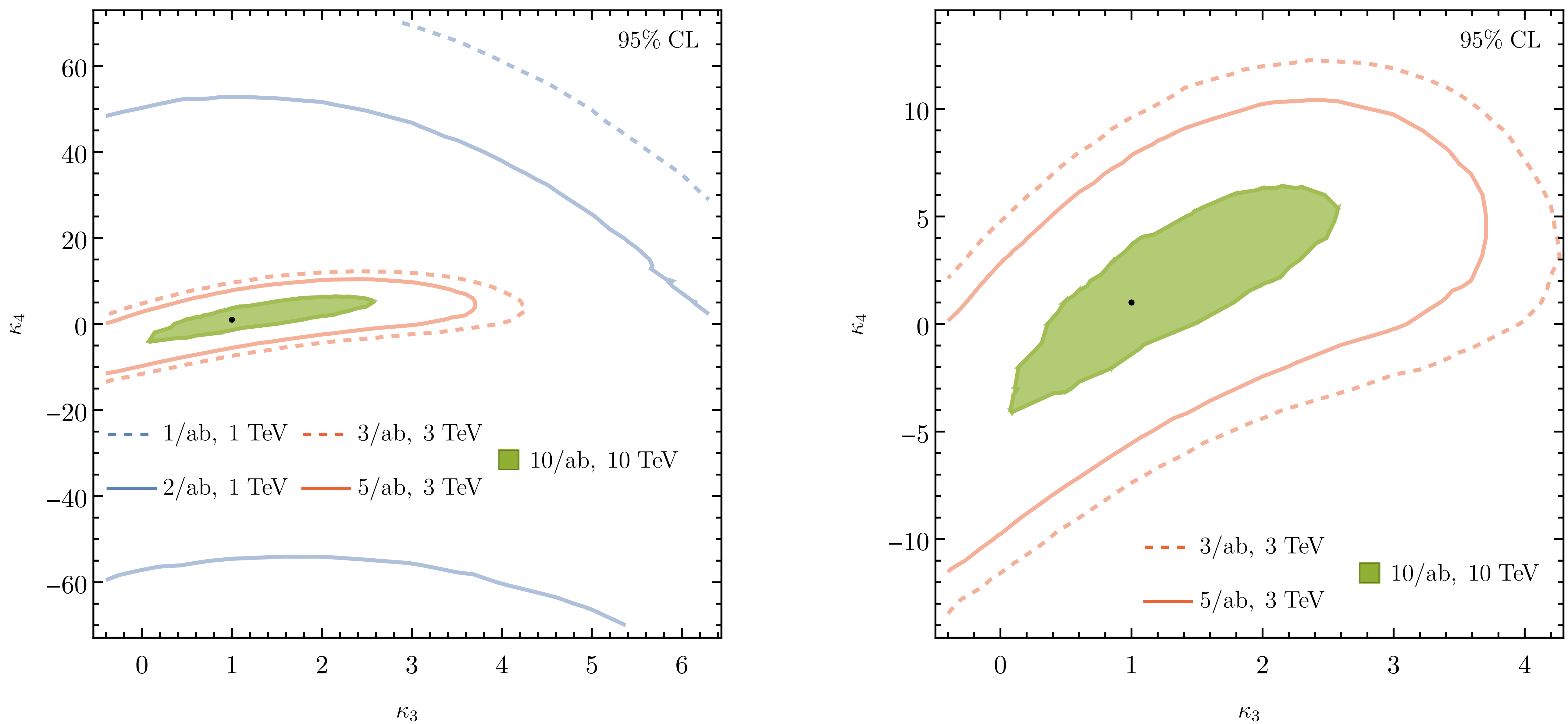
- Negligible background from other SM processes



Higgs self-couplings at lepton colliders

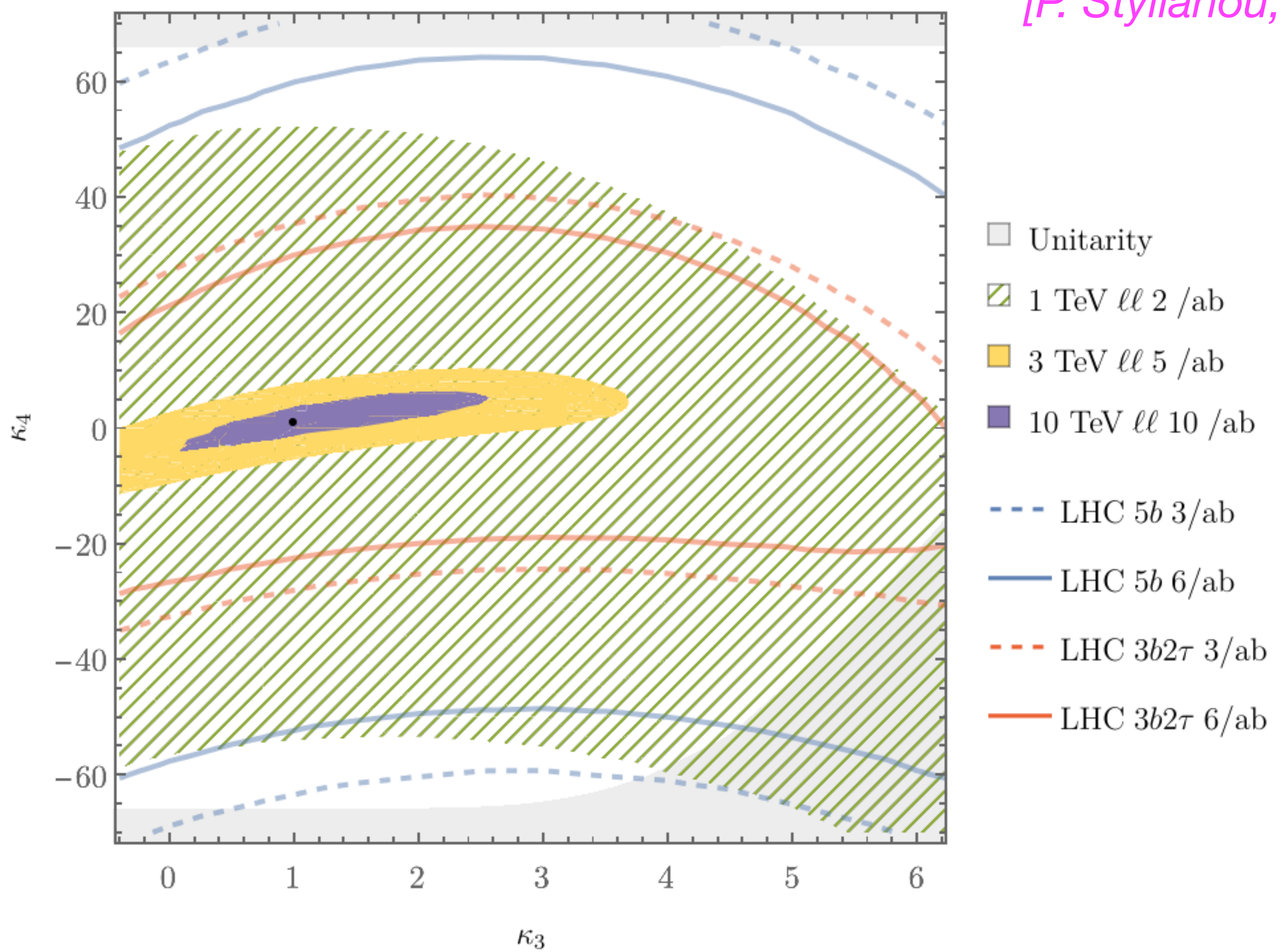
[P. Stylianou, G. W. '24]

- Poissonian analysis: $\mu_{\rm up} = \frac{1}{2} F^{-1}_{\chi^2}\left[2(n+1); {\rm CL}\right]$
- Results similar to other works with dedicated analyses for 1 and 3 TeV, e.g. [Maltoni, Pagani, Zhao ` 18]



Triple Higgs production: HL-LHC vs. lepton colliders

[P. Stylianou, G. W. '24]



HL-LHC is competitive to 1 TeV lepton collider; higher-energetic lepton colliders have better sensitivity

BSM Higgs bosons

Compatibility of extended Higgs sectors with exp. results:

- A SM-like Higgs at ~125 GeV
- Properties of the other Higgs bosons (masses, couplings, …) have to be such that they are in agreement with the present bounds

⇒ Additional Higgs bosons may well be lighter than the SM-like Higgs boson (h125)

If h125 is the lightest state of an extended Higgs sector, a typical feature is that the other states are nearly mass-degenerate and show ``decoupling” behaviour

At lepton colliders heavy BSM Higgses are typically pair-produced
⇒ Best prospects at highest c.m. energy!

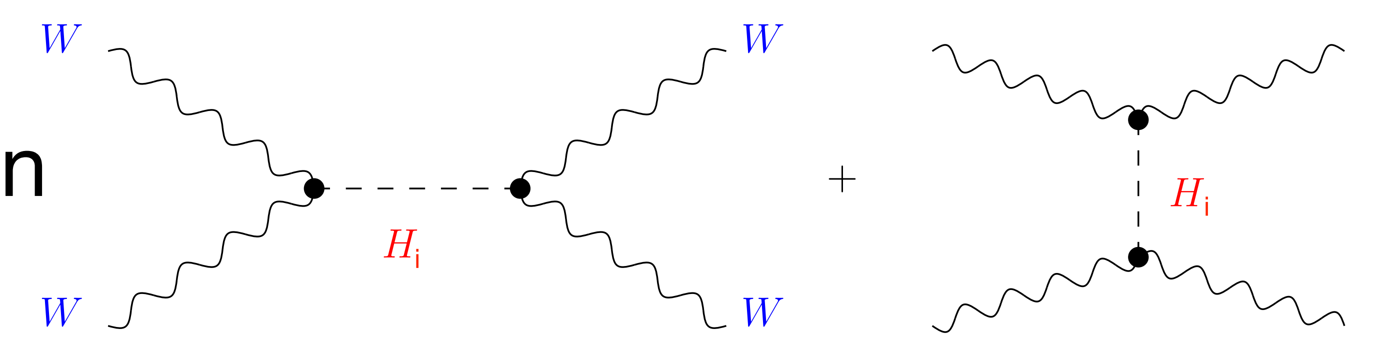
Search for additional Higgs bosons

In a large variety of models with extended Higgs sectors the squared couplings to gauge bosons fulfill a ``sum rule":

$$\sum_i g^2_{H_i VV} = \left(g^{\rm SM}_{HVV}\right)^2$$

The SM coupling strength is ``shared" between the Higgses of an extended Higgs sector, $\varkappa_V \leqq 1$

⇒ Unitarisation of the vector boson scattering amplitudes



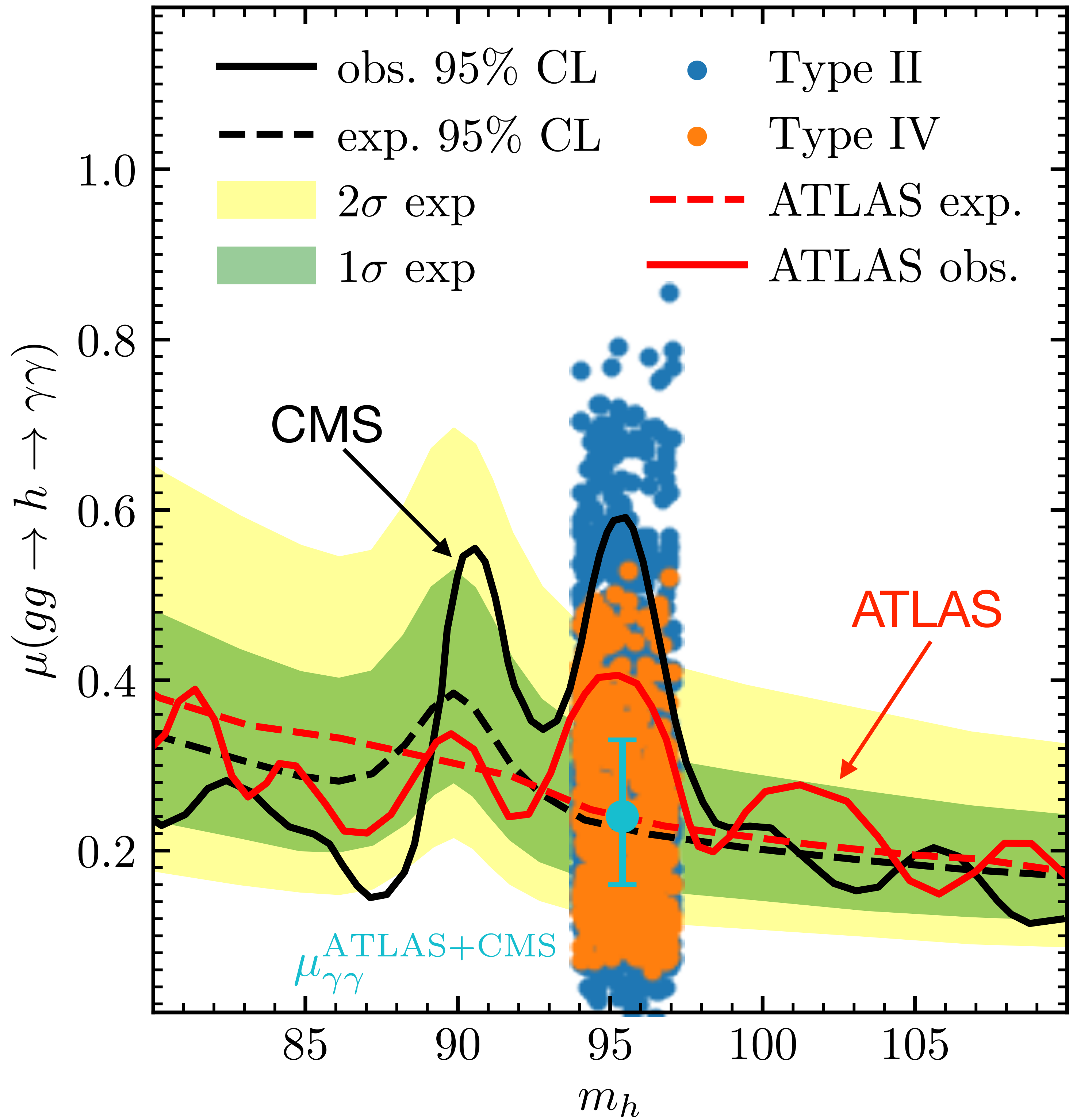
⇒ The more SM-like the couplings of the state at 125 GeV turn out to be, the more suppressed are the couplings of the other Higgses to gauge bosons

⇒ Heavy Higgs bosons usually have a much smaller total width than a SM-like Higgs of the same mass

BSM Higgs: CMS + ATLAS excess in $\gamma\gamma$ channel at 95 GeV, interpretation in 2HDM + singlet (S2HDM)

S2HDM, type II and IV:

[T. Biekötter, S. Heinemeyer, G. W. '23]

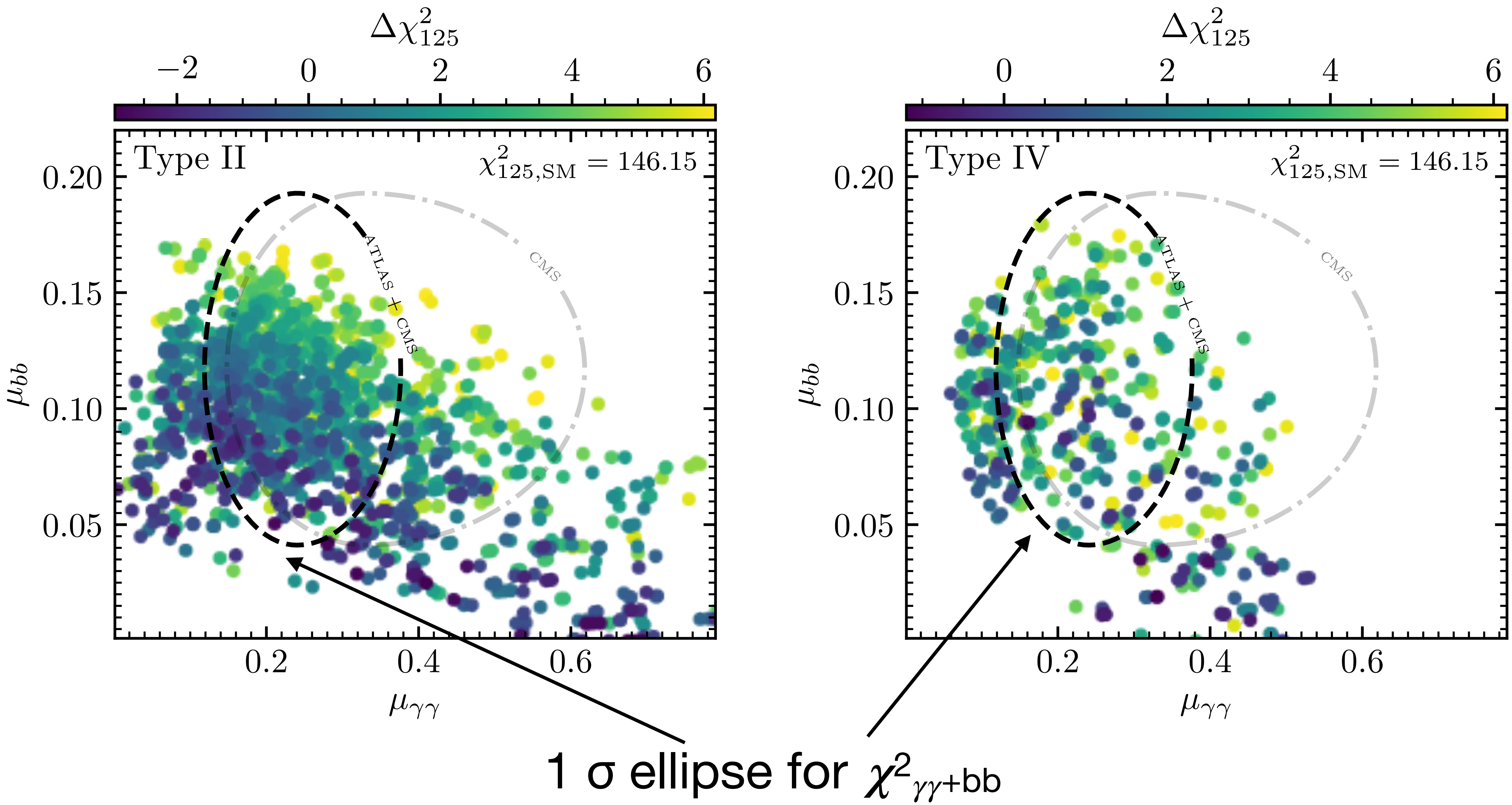


$\Rightarrow$ Good description of the observed excesses

Excesses near 95 GeV at the LHC and at LEP

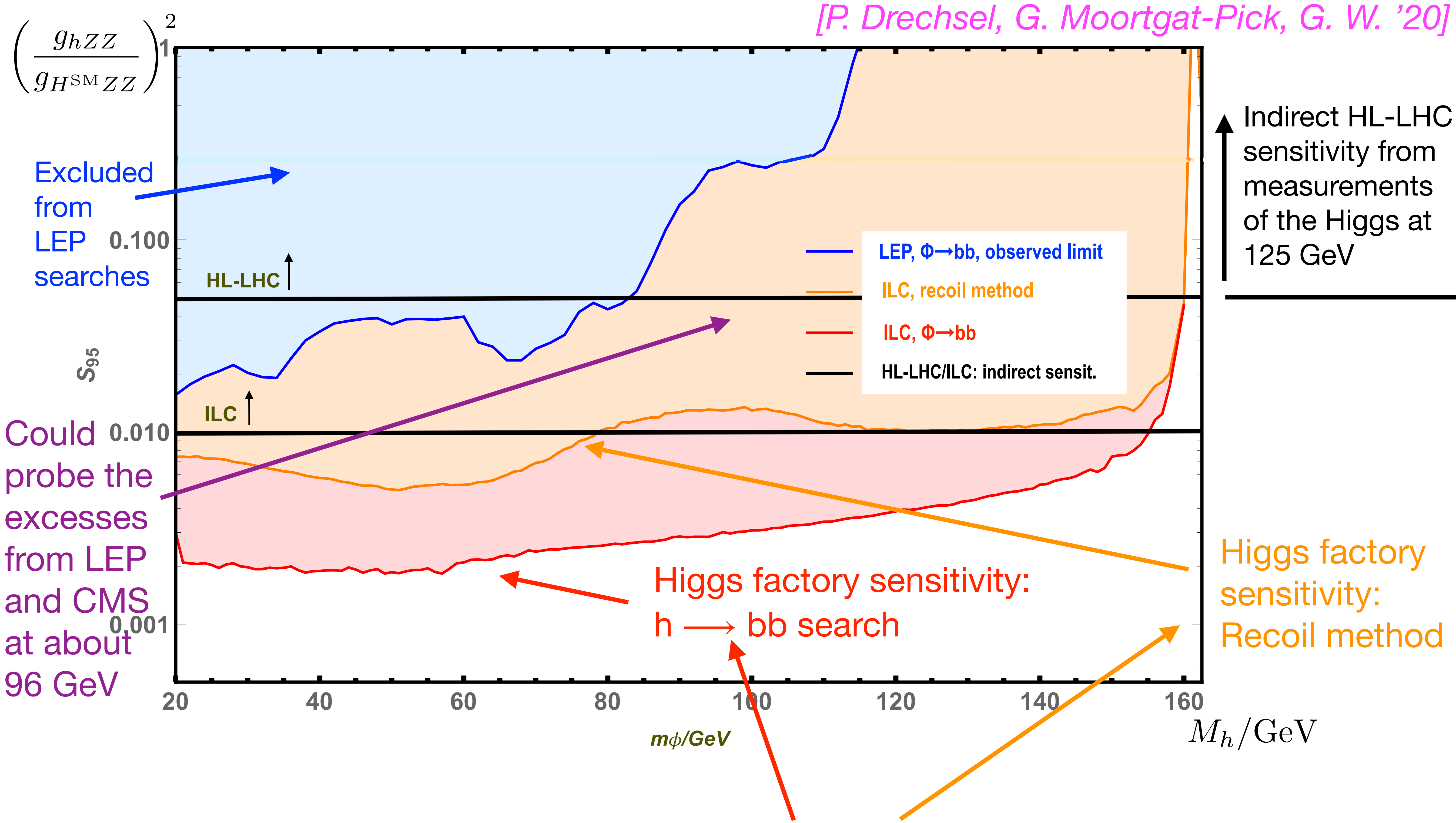
S2HDM, type II and IV:

[T. Biekötter, S. Heinemeyer, G. W. '23]



⇒ The LHC excess in the $\gamma\gamma$ channel and the LEP excess in the bb channel can be described very well simultaneously!

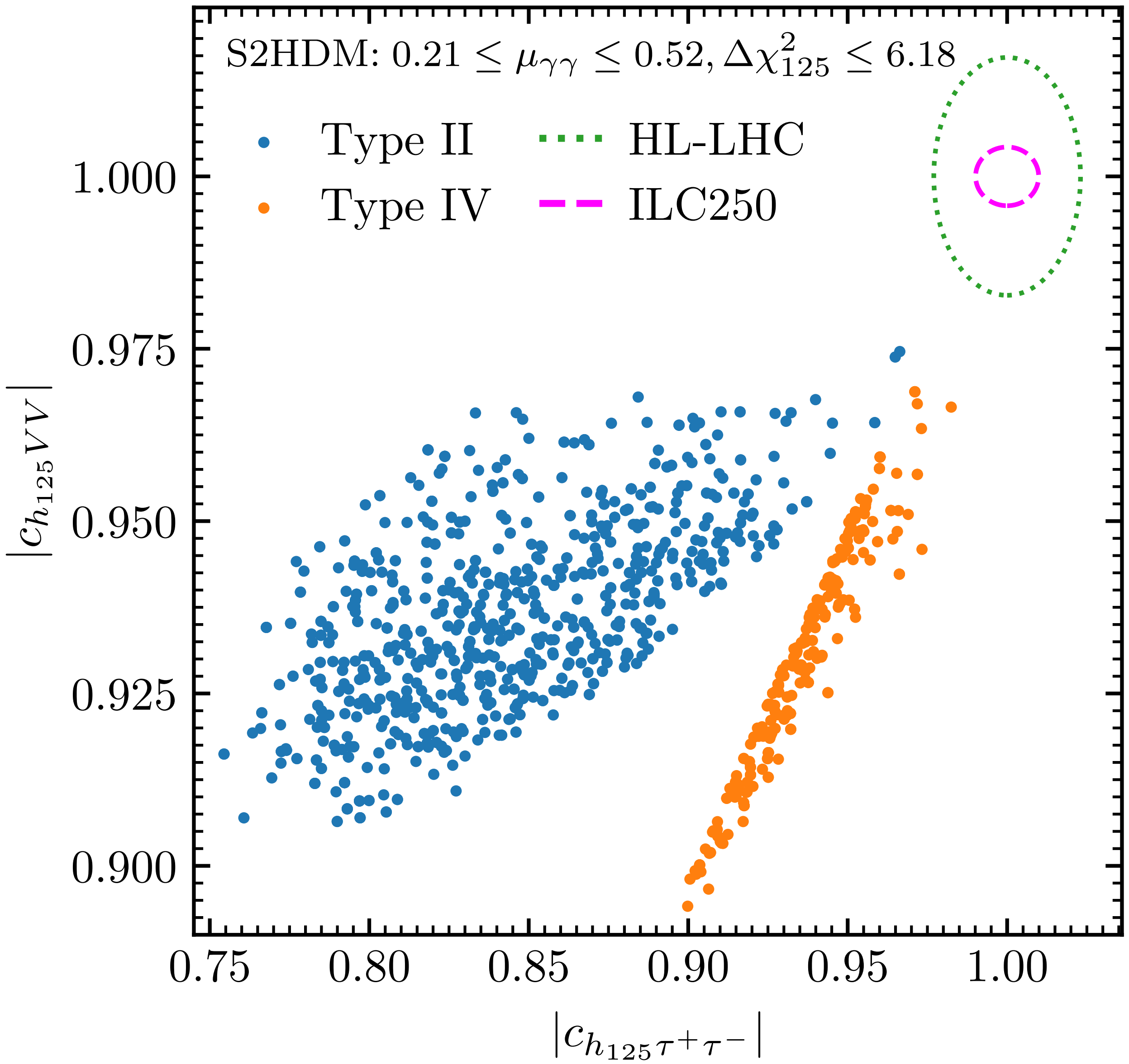
Higgs factory: discovery potential for a low-mass Higgs; Sensitivity at 250 GeV with 500 fb^{-1}

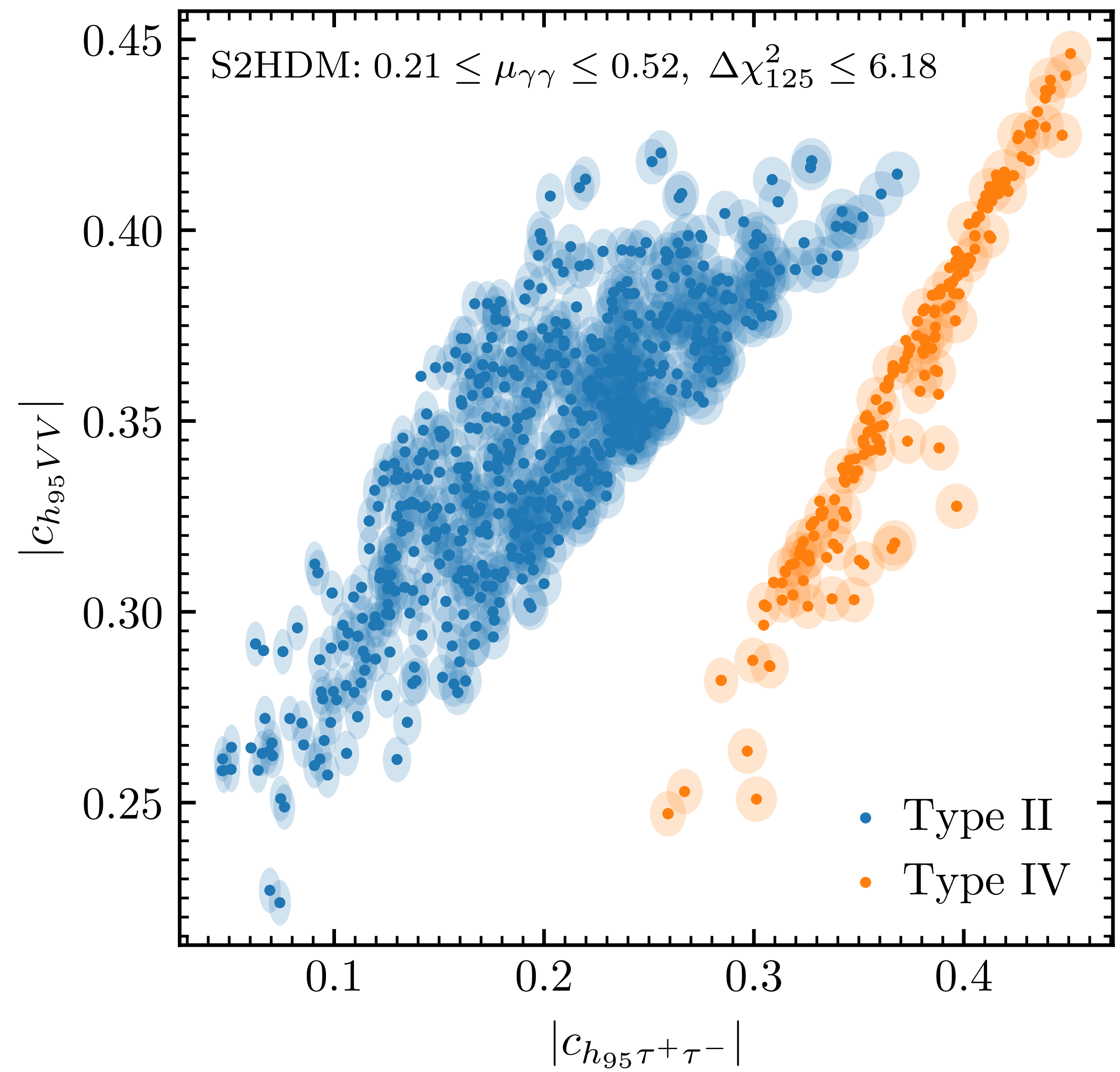


⇒ Higgs factory at 250 GeV will explore a large untested region!

Prospects for coupling measurements of h125 and h95 at an e^+e^- Higgs factory

S2HDM, type II and IV: *[T. Biekötter, S. Heinemeyer, G. W. '23]*





⇒ Precision measurements of the couplings of both h125 and h95
High sensitivity to the realised physics scenario (Yukawa type, …)

Conclusions

Higgs physics at future colliders (with a broad brush):

- e^+e^- Higgs factory at low energy: precise measurements of the couplings of h125 to fermions and gauge bosons, high sensitivity for additional light Higgs bosons

- Additional physics programme of e^+e^- Linear Collider with c.m. energy of at least 500 GeV: exploration of the Higgs potential, good prospects for the production of heavy additional Higgs bosons

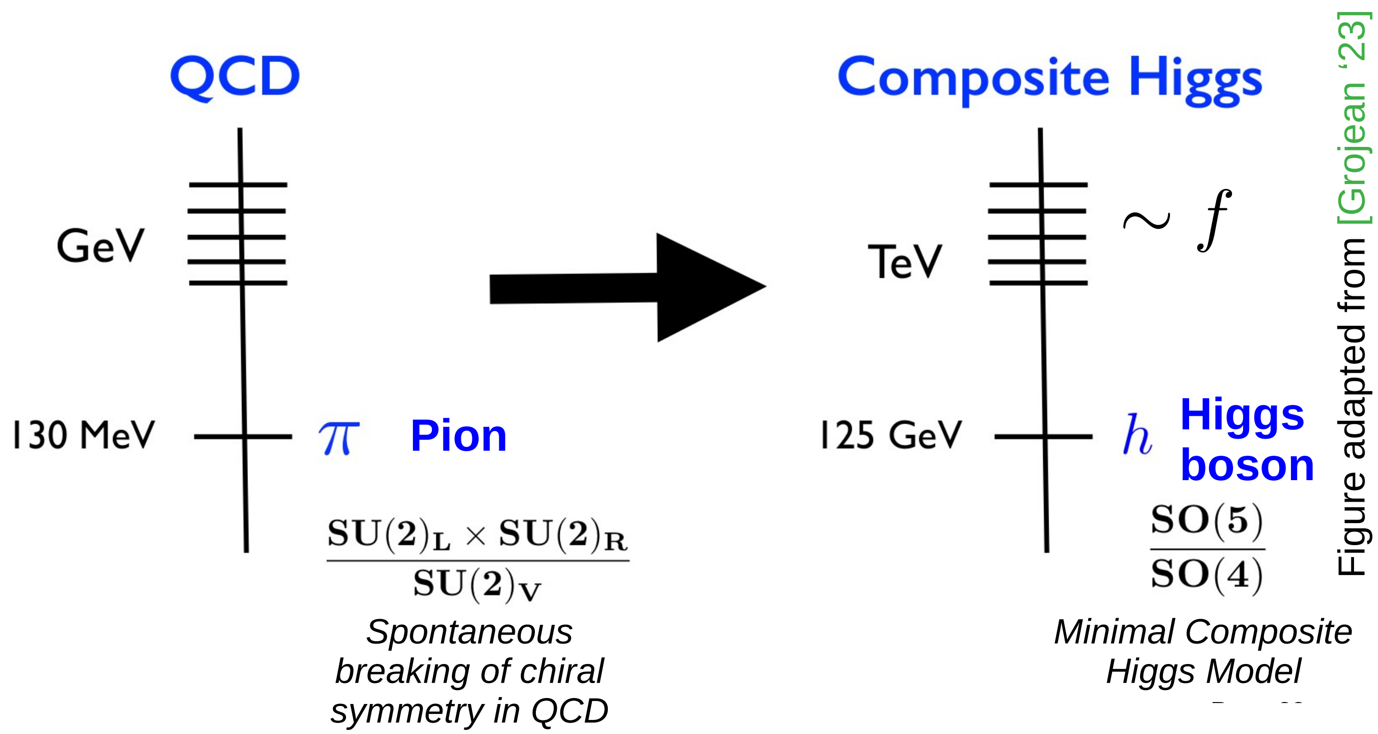
- Highest-energetic lepton colliders: sensitivity for constraining the quartic Higgs self-coupling

Backup

Composite PGB, identified with the Higgs boson

Composite Higgs models can be viewed as an interpolation between a weakly coupled Higgs model and a strongly coupled technicolour model

Composite Higgs is a bound state, similar to the pion in QCD



Mass of the bound state is not sensitive to virtual effects above the compositeness scale

Higgs mass measurement: the need for high precision

Measuring the mass of the discovered signal with high precision is of interest in its own right

But a high-precision measurement has also direct implications for probing Higgs physics

M_H (H = h125): crucial input parameter for Higgs physics

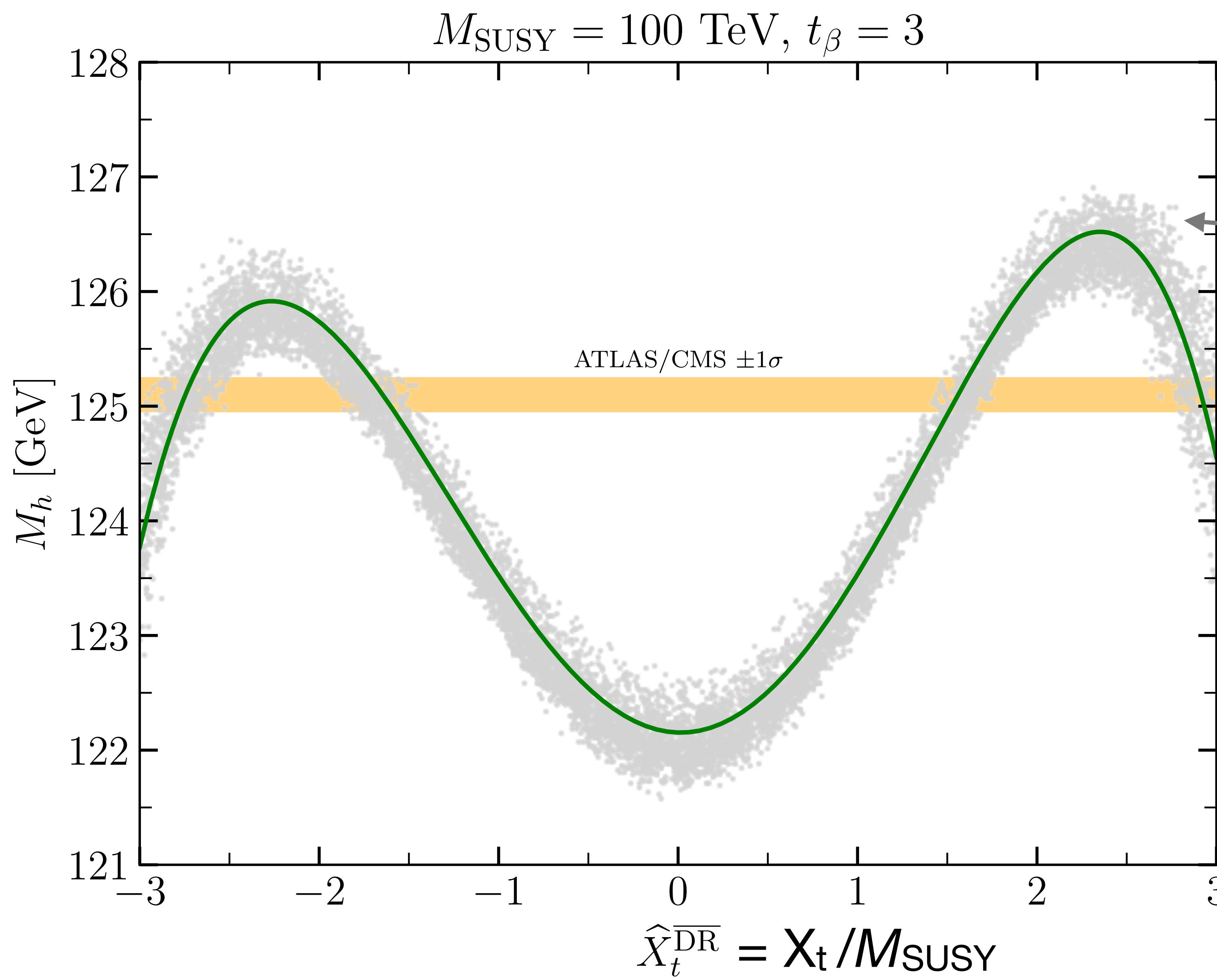
BR(H → ZZ^*), BR(H → WW^*): highly sensitive to precise numerical value of M_H

A change in M_H of 0.2 GeV shifts BR(H → ZZ^*) by 2.5%!

⇒ Need high-precision determination of M_H to exploit the sensitivity of BR(H → ZZ^*), ... to test BSM physics

Higgs mass prediction vs. experimental result

Higgs mass as a precision observable: M_{h125} = 125.25 ± 0.17 GeV
Comparison: M_h prediction for heavy SUSY (M_{SUSY} = 100 TeV)



[H. Bahl, J. Braathen, G. W. '22]

Mass parameters and trilinear couplings varied in [1/2 M_{SUSY}, 2 M_{SUSY}]

X_t : mixing in the scalar top sector

⇒ High-precision measurement of the Higgs mass puts important constraints on BSM physics even if new physics scale is very high!

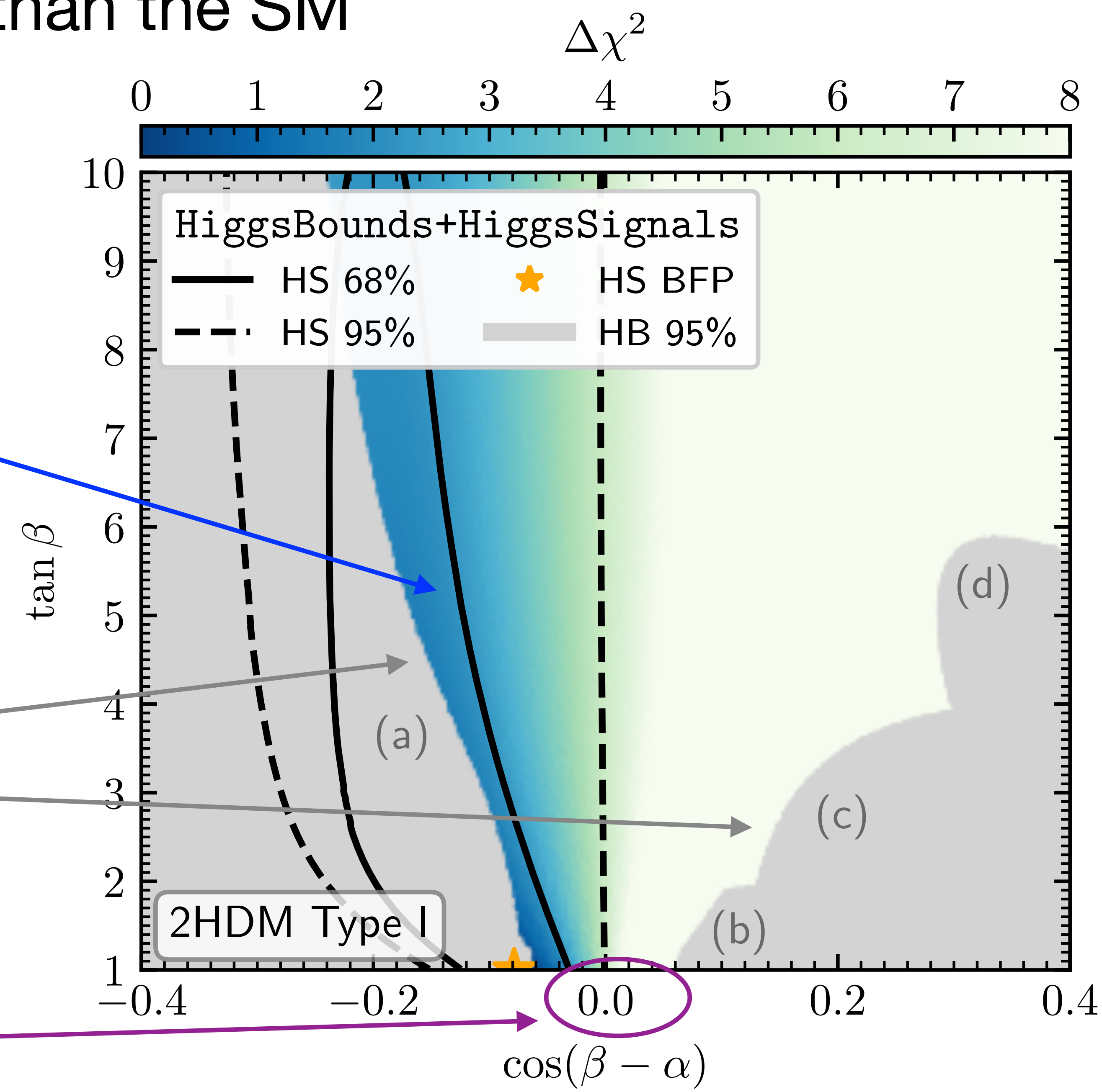
Probing the SM and extended Higgs sectors

The experimental results indicate that the observed state h125 has SM-like properties, but extensions of the SM may have a higher compatibility with the data than the SM

Example: 2HDM of type I
[H. Bahl et al. ’22]

Preferred region from Higgs measurements

Limits from Higgs searches



SM limit (alignment)

⇒Alignment limit disfavoured, slight preference for non-zero BSM contrib.

Discovery potential of ILC 250 for invisible decays and decays that are "undetectable" at the LHC

Direct search for H → invisible at ILC 250 has sensitivity down to branching ratios 0.3%

If there are dark matter particles with a mass below half of the Higgs mass, then the Higgs decay into a pair of those particles will give rise to an invisible decay mode

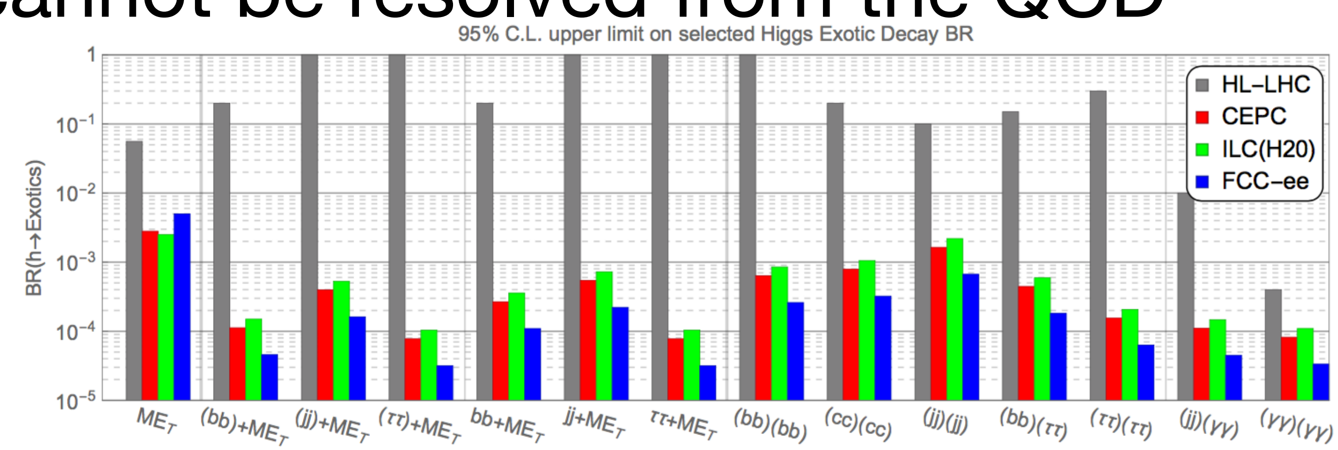
⇒ Discovery potential for dark matter and other new physics

Complementary sensitivity via high-precision measurements of the Higgs couplings: the presence of an invisible decay mode leads to a simultaneous suppression of all other branching ratios!

Also sensitivity at the %-level to decays that are "undetectable" at the LHC: decay products that cannot be resolved from the QCD background (non-b jets, gg, …)

"Exotic" decay modes: large improvements over HL-LHC

[Z. Liu, L.T. Wang, H. Zhang '17]



CP properties of h125

⇒ Observables involving the *HVV* coupling provide only limited sensitivity to effects of a CP-odd component, even a rather large CP-admixture would not lead to detectable effects in the angular distributions of $H \to ZZ^* \to 4\,l$, etc. because of the smallness of a_3

Hypothesis of a pure CP-odd state is experimentally disfavoured

However, there are only weak bounds so far on an admixture of CP-even and CP-odd components

Channels involving only Higgs couplings to fermions have the potential to provide much higher sensitivity

Vacuum stability of extended Higgs sectors (T = 0)

Extended Higgs sectors with additional minima of the scalar potential at the weak scale that may be deeper than the EW vacuum

⇒ Tunneling from EW vacuum to deeper vacua possible depending on the ``bounce action" B (stationary point of the euclidian action) for the tunnelling process

⇒ EW vacuum can be short-lived, metastable or stable

Decay rate per spatial volume: $$\frac{\Gamma}{V_S} = K e^{-B}$$

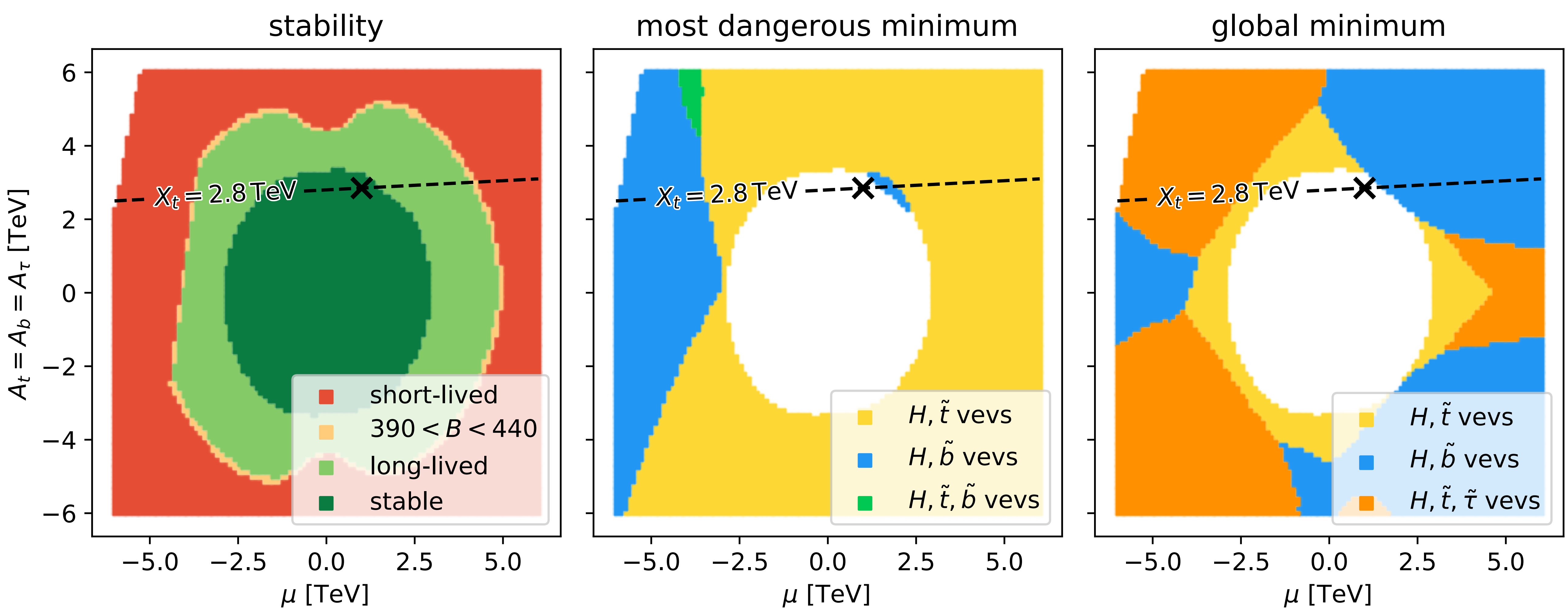
``Most dangerous minimum": highest tunnelling rate from EW vacuum

Constraints from vacuum stability at T = 0 can be combined with the ones from the thermal evolution of the Universe (see below)

Vacuum stability constraints in the MSSM

[W.G. Hollik, J. Wittbrodt, G. W. '18]

Parameter plane around example point of M_h^{125} benchmark scenario



⇒ Particularly important: instabilities in directions with sfermion vevs (charge or colour-breaking minima, CCB)

Character of most-dangerous minimum differs from global minimum

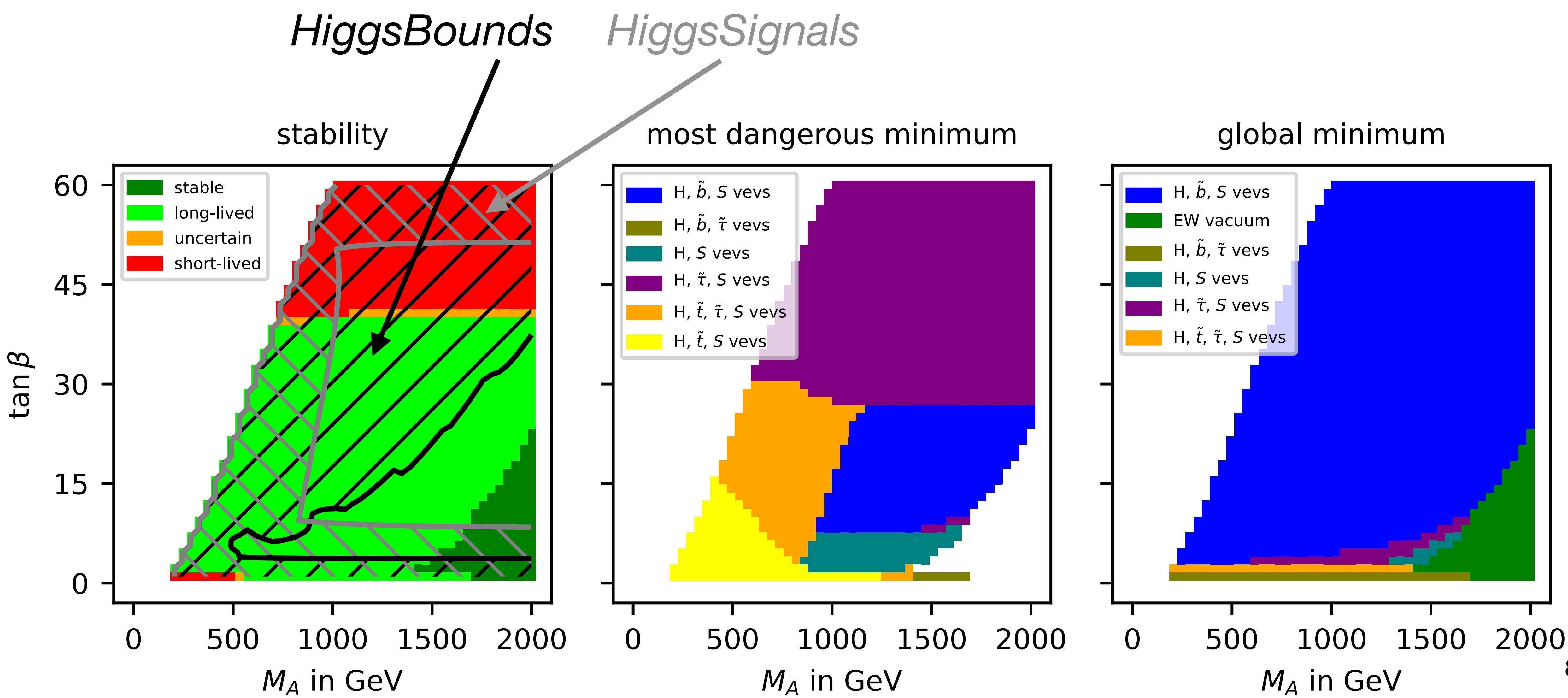
Region of absolute stability and global minimum sensitively depend on fields with small couplings to the Higgs

Vacuum stability constraints in the NMSSM

Improved version of the public code *Evade* *[W.G. Hollik, G. W., J. Wittbrodt ’18]*

Example: constraints from vacuum stability in the NMSSM on the region allowed by *HiggsBounds* and *HiggsSignals*

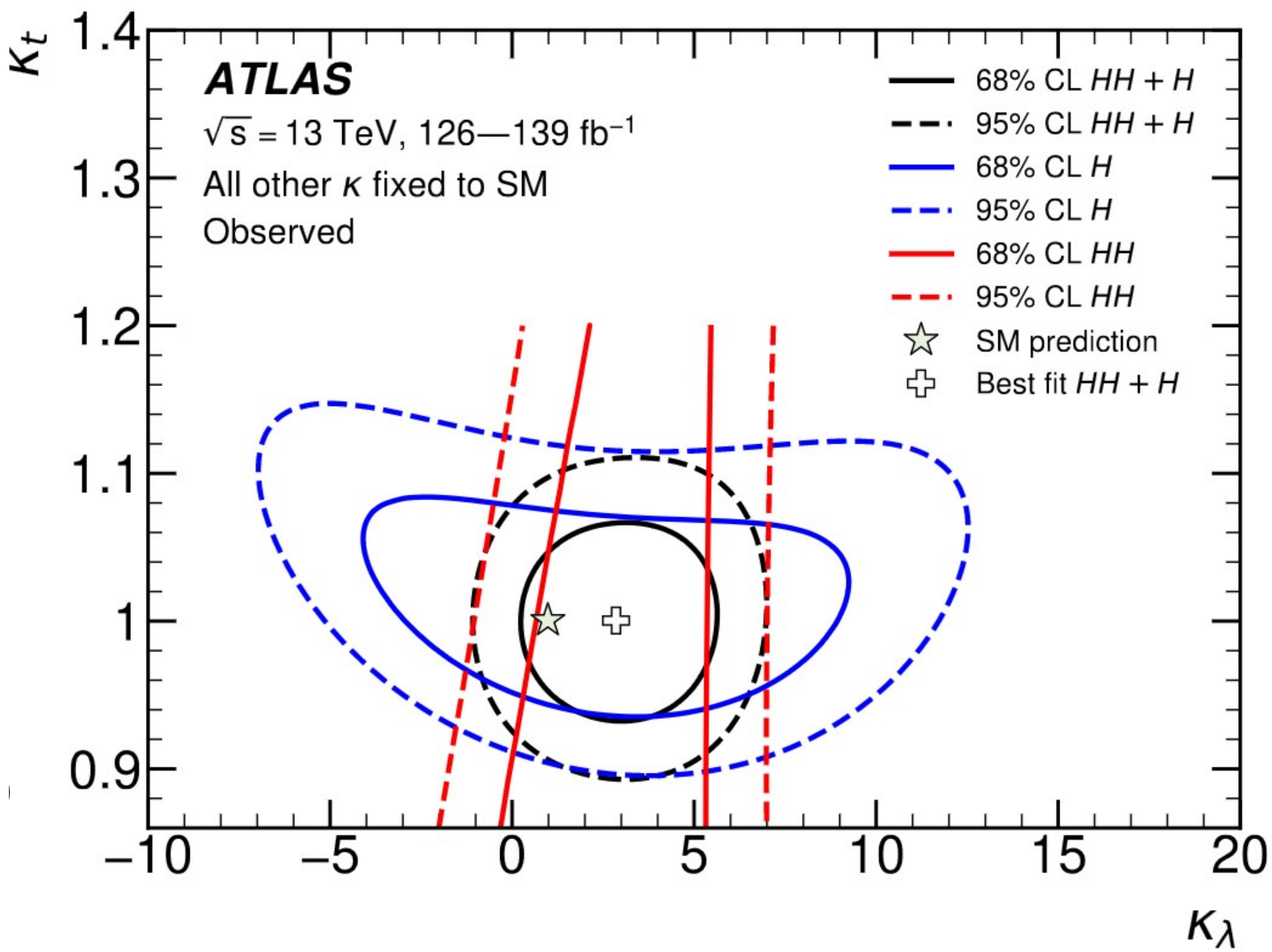
[T. Biekötter, F. Campello, G. W. ’24]



Experimental constraints on $\varkappa_\lambda$

[ATLAS Collaboration ’22]

Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.5$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.3 < \kappa_\lambda < 6.1$	$-2.1 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

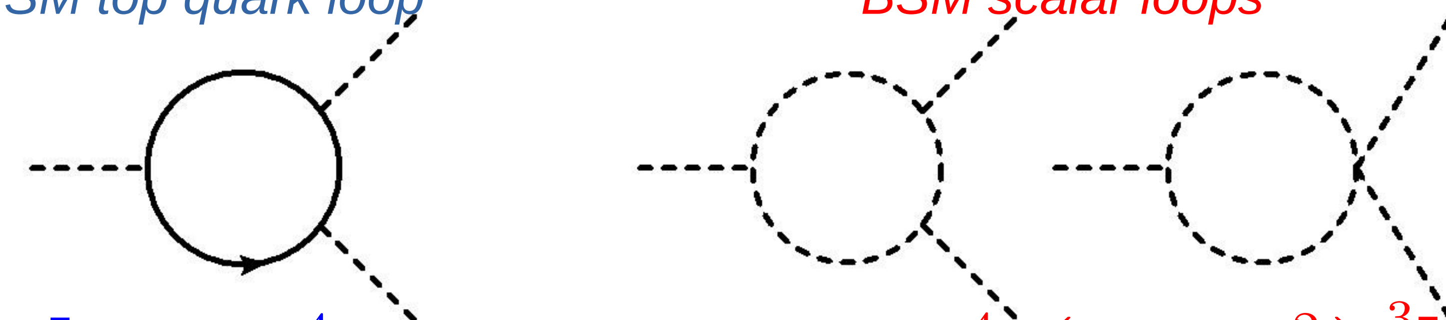


Effects of BSM particles on the trilinear Higgs coupling

Trilinear Higgs coupling in extended Higgs sectors: potentially large loop contributions

- **Leading one-loop** corrections to λ_{hhh} in models with extended sectors (like 2HDM):

SM top quark loop *BSM scalar loops*



$$\delta^{(1)}\lambda_{hhh} \supset \frac{1}{16\pi^2}\left[-\frac{48m_t^4}{v^3} + \sum_\Phi \frac{4n_\Phi m_\Phi^4}{v^3}\left(1-\frac{\mathcal{M}^2}{m_\Phi^2}\right)^3\right]$$

First found in 2HDM:
[Kanemura, Kiyoura, Okada, Senaha, Yuan '02]

$\mathcal{M}$: **BSM mass scale**, e.g. soft breaking scale M of Z_2 symmetry in 2HDM
n_Φ : # of d.o.f of field Φ

- Size of new effects depends on how the BSM scalars acquire their mass: $m_\Phi^2 \sim \mathcal{M}^2 + \tilde{\lambda}v^2$

⇒ Large effects possible for sizeable splitting between m_Φ and $\mathcal{M}$

Single-Higgs processes: λ enters at loop level

[E. Petit '19]

How to measure deviations of λ_3

- The Higgs self-coupling can be assessed using di-Higgs production and single-Higgs production
- The sensitivity of the various future colliders can be obtained using four different methods:

	di-Higgs	single-H
exclusive	**1. di-H, excl.** • Use of σ(HH) • only deformation of κλ	**3. single-H, excl.** • single Higgs processes at higher order • only deformation of κλ
global	**2. di-H, glob.** • Use of σ(HH) • deformation of κλ + of the single-H couplings (a) do not consider the effects at higher order of κλ to single H production and decays (b) these higher order effects are included	**4. single-H, glob.** • single Higgs processes at higher order • deformation of κλ + of the single Higgs couplings

Note: this is based on the assumption that there is a large shift in λ, but no change anywhere else!

Single-Higgs processes: λ enters at loop level

[B. Heinemann '19]

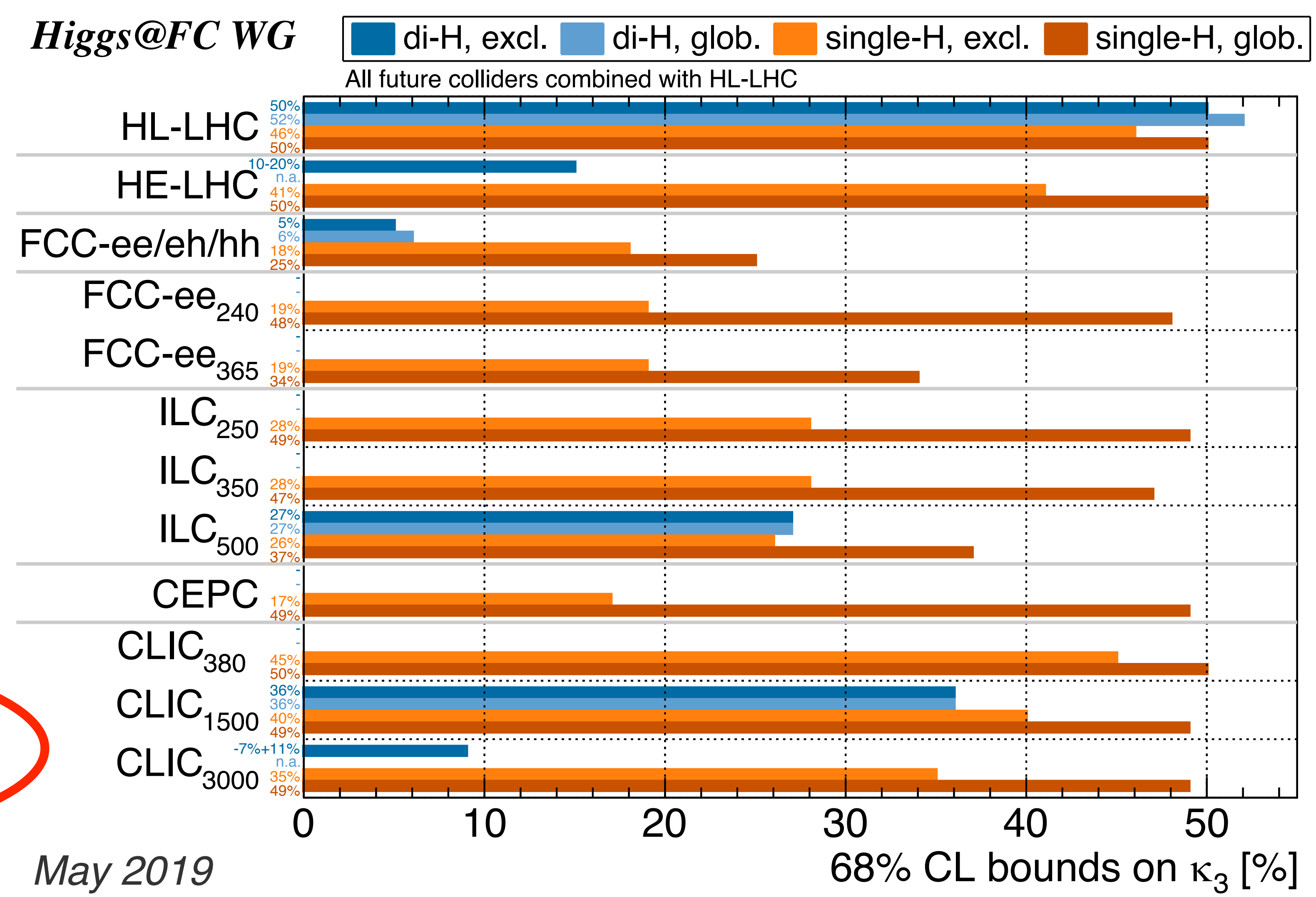
Sensitivity to λ: via single-H and di-H production

Di-Higgs:

- **HL-LHC: ~50% or better?**
- **Improved by HE-LHC (~15%), ILC_{500} (~27%), $CLIC_{1500}$ (~36%)**
- **Precisely by $CLIC_{3000}$ (~9%), FCC-hh (~5%),**
- **Robust w.r.t other operators**

Single-Higgs:

- **Global analysis: FCC-ee365 and ILC500 sensitive to ~35% when combined with HL-LHC**
  - **~21% if FCC-ee has 4 detectors**
- **Exclusive analysis: too sensitive to other new physics to draw conclusion**



Prospects for the HL-LHC

- Use of Graph Neural Networks (GNN) for signal-background classification

- Focus on $6b$ and $4b2\tau$ final states with 5 and 3 tagged b-quarks, respectively

Backgrounds:

$6b$: dominant QCD contributions (see also [Papaefstathiou, Robens, Xolocotzi` 21])

$4b2\tau$: $W^+W^-b\bar{b}b\bar{b},\ Zb\bar{b}b\bar{b},$

$t\bar{t}(H \to \tau\tau),\ t\bar{t}(H \to b\bar{b}),$

$t\bar{t}(Z \to \tau\tau),\ t\bar{t}(Z \to b\bar{b}),\ t\bar{t}t\bar{t}$

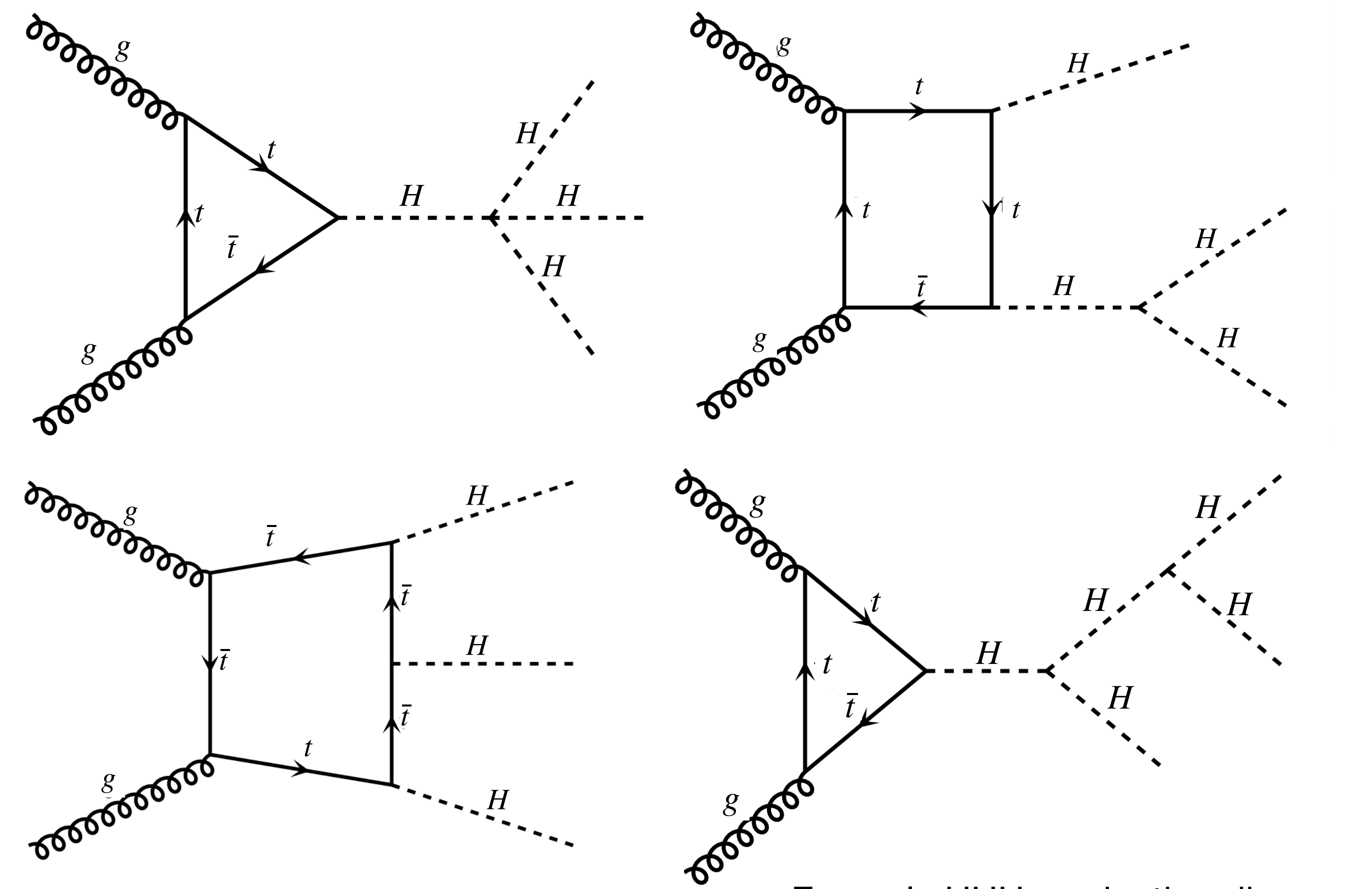
Event generation and pre-selection

- Events generated with MadGraph5_aMC@NLO
- Higgs states decayed with MadSpin

(conservative) background K-factor of 2

signal K-factor of 1.7

[Florian, Fabre, Mazzitelli` 20]



Example HHH production diagrams

Pre-selection cuts:

Invariant mass of final states: $\gtrsim 350$ GeV

At least one pair of tagged states with

$m_{ij} \in [110,140]$

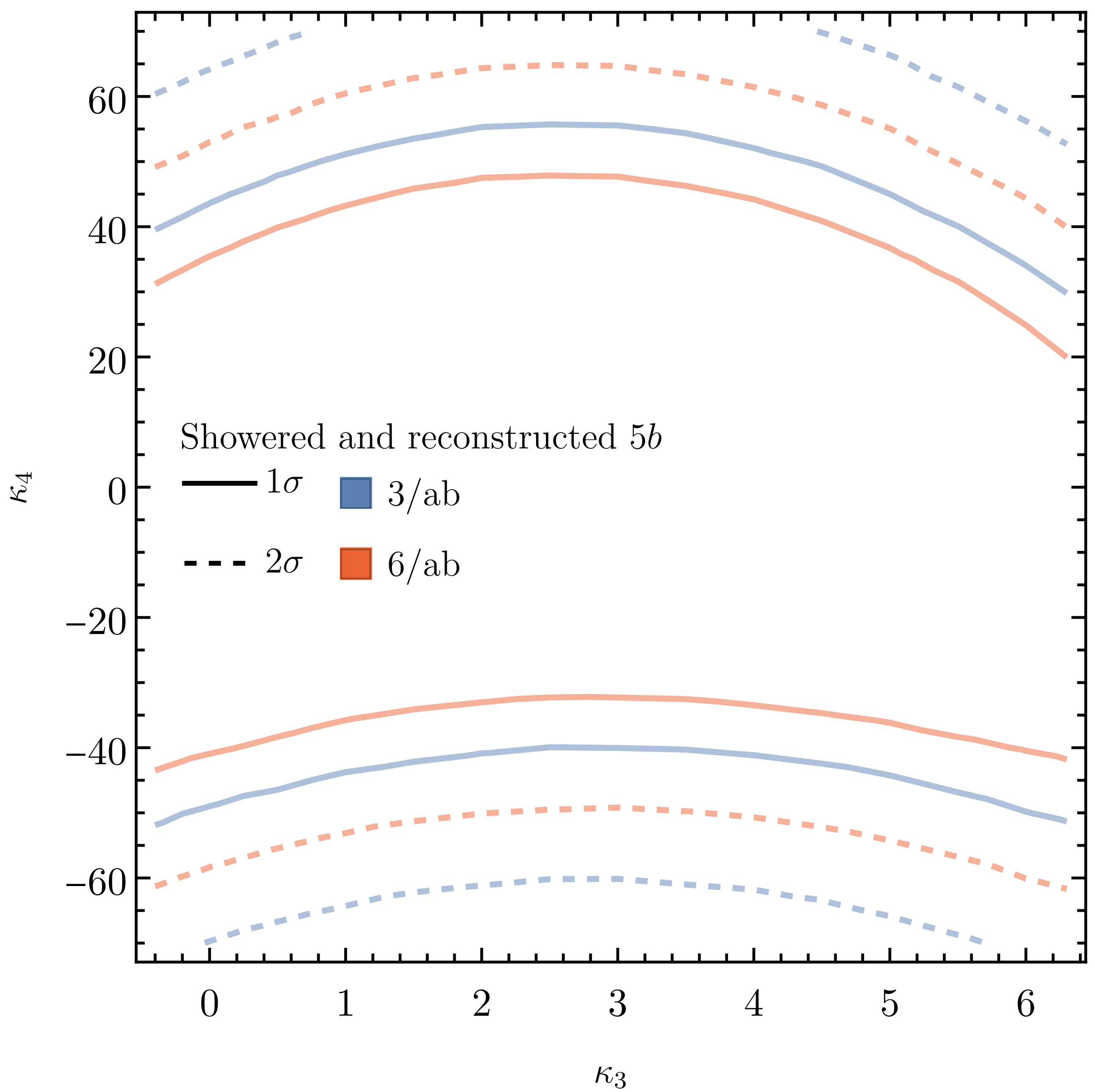
$p_T(b) > 30$ GeV $\quad p_T(\tau) > 10$ GeV

$|\eta(\tau)| < 2.5 \quad |\eta(b)| < 2.5$

Showered and reconstructed results: 5b

- Showering and reconstruction of events: Pythia, FastJet, Rivet
- HL-LHC luminosity of $3/\text{ab}$ and ATLAS-CMS combined luminosity of $6/\text{ab}$

Signal region selected with cut on background score $P[QCD] \lesssim 0.5\,\%$



Showered and reconstructed results: 3b2τ

- $3b2\tau$ more complicated due to multiple backgrounds → multi-class classification
- Train on backgrounds: $W^+W^-b\bar{b}b\bar{b},\ Zb\bar{b}b\bar{b},\ t\bar{t}(H \to \tau^+\tau^-)$